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physical properties of alpine snow as related to weather and avalanche conditions

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ABSTRACT

Data were taken in avalanche starting zones at an elevation of 11,700 feet in Front Range of Colorado within 14 days of deposition. Densities varied from 40 to 450 kg m^{-3}. A statistical criterion was used to identify snow with unusually high density for its age (initial hard slab) and unusually low (persistent soft snow). Initial hard slab, found in 15 percent of the pits, was correlated with moderate to high windspeeds, low temperatures, and presence of wind-transported snow. No good way was found to distinguish initial hard slab from dense older snow. Tensile strength from a spin test varied from 1.0 to 1712 grams force cm^{-2}. Strength increased with density but varied greatly for given density. Younger snows tended to be weaker than older snows of same density. Strength was also measured with shear box and shear vane. Ram resistance was higher for alpine snow than for snow of same density in the trees. Air permeability was an order of magnitude less than expected and varied with the low flow rate used. The ratio virtual porosity/porosity, which averaged 1.062, was of little value for identifying wind slab. Strength of snow of given density was greater for a certain permeability (texture) than for any other.

KEY WORDS: Avalanches, snow, weather, permeability, snow density.

ABOUT THE COVER:

This hard-slab avalanche was released in the study area 19 Feb 1966 by an explosive charge. The fracture face in the shadowed area is 7 feet tall. The avalanche slid over an old snow surface in the top of the track, but went to ground farther down the 600-foot-long track. Angular blocks in the debris are typical of hard-slab avalanches. The fact that many of the blocks could be fitted back together suggests brittle failure of the snow. The ripples and pockmarks on the snow surface outside the slide area are the result of wind action.

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Physical Properties of Alpine Snow as Related to Weather and Avalanche Conditions

by

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Background

The avalanche classification proposed by de Quervain (1966) and used in many countries differentiates between hard slab and soft slab avalanches.[2] The field designation for hard or soft slab is usually based on the size and shape of the debris left by the avalanche. Distinct angular blocks of snow in the debris indicate hard slab, while amorphous mounds or sheets of debris distinguish the soft slab—provided, of course, the telltale fracture line of the slab avalanche is present in the starting zone.

It is generally agreed that wind action, either during snowfall or during the transport and redeposition of old snow, toughens the snow and often leads to slab formation. Seligman (1936) says soft slab forms when the amount of precipitation or drift snow is too great for the wind to pack solidly. Hard slab, according to him, is the result of the amount of icing (cementing or bonding), which he attributes to the duration and intensity of winds. Others (U.S. Forest Service 1961) have said that, although wind is one of the predominant natural factors in slab formation, wind alone is neither necessary nor sufficient to cause slab formation in snow-covered areas.

LaChapelle (1966) states that hard slab is the principal type of avalanche in the Rocky Mountain region of the United States, and implies it is the result of cold temperatures and strong winds. Judson (1967) agrees that hard slab is often formed in Colorado during periods of light snowfall and cold temperatures. He points out, however, that soft-slab avalanches outnumber hard-slab avalanches three to one in Central Colorado—a proportion common to many areas.

Although there seems to be considerable doubt about the frequency, distribution, and cause of hard slab formation, practical experience has shown that the operational procedures necessary to maintain safety on winter sports areas and along mountain highways are different for hard-slab and soft-slab conditions. For example, when hard slab is present:

1. Slope stabilization by protective skiing is difficult and very uncertain.
2. Explosive control is also difficult because hard slab is often highly localized. For this reason, an avalanche released on one slide path seldom propagates to other paths, as often happens with more widespread soft slab. This means each danger spot must be controlled directly.
3. Heavier than usual explosive charges are needed because of the greater strength of hard slab.
4. Different target areas become important.

It is of more than academic interest, therefore, to be able to determine the type of slab present before an avalanche runs, and to know more about the weather conditions causing different types of slab.

[2] The term slab avalanche is the English translation of the German term Schneebrett-lawine and refers to avalanches of snow with an appreciable degree of internal bonding (Mellor 1968).

Objectives

This study was undertaken (1) to determine the physical and mechanical properties of newly deposited snow, and (2) to correlate these properties with the weather factors during deposition, with special emphasis on the factors leading to hard slab. More specifically, we wanted to see (1) if the ratio of virtual porosity to actual porosity (Bader 1954) could be used to identify wind slab; (2) what wind, temperature, and precipitation conditions were important for the two types of slab; and (3) what mechanical or physical properties could be used to distinguish hard from soft slab without having to wait for an avalanche to run.

Study Site and Data Taken

Data were taken in the starting zones of several small avalanches at an elevation of 11,700 feet, near Berthoud Pass in the Front Range of Central Colorado (fig. 1).

Slopes were steep (average gradient about 35°) and rocky, with a sparse cover of grasses, sedges, and forbs. Exposures varied from north through east. Scattered islands of short, wind-trimmed spruce and fir trees (Krummholz) were present around the edges of several of the avalanche paths. The upper limit of erect tree growth was 250 to 300 feet below the study site. Within 5 miles of the site there are 55 avalanche paths that cross interstate highways, or threaten mining operations, homes, or public ski areas. There are 74 such paths within 10 miles, and 112 within 15 miles.

The following weather data were available either from the routine climatic observations being taken at the Pass, or as a part of this study:

> Windspeed and direction were taken 6 feet above the snow, 75 to 100 feet uphill from the study area; air temperature and precipitation were recorded and snow depths measured daily in a small opening in the timber 400 feet below and 1/4 mile northeast of the study site; new snow depths were measured at intervals of several days on stakes located in the study area.

At selected spots, specific snowcover data were taken following two storms in the winter 1964-65, one in 1965-66, eight in 1966-67, and seven in 1967-68. One additional set of data was gathered at the Urad Mine 4 miles southwest of the study

Figure 1.--Study site in the Front Range of Colorado. Berthoud Pass, where U. S. Highway 40 crosses the Continental Divide, is in the lower left foreground. The avalanche path called the Roll is the smooth, curving slope marked A. Q-12 Park where climatic data were taken is the small opening in the trees marked B.

site in March 1965. For the last two winters, data were gathered for most of the significant storms. These data included:

> Ram resistance, snow stratigraphy, snow temperature, grain size, grain type, snow density, air permeability, and three independent indexes of strength.

Ram resistance was usually measured for the entire depth of the snow cover. Other items were measured for each significant layer within the new snow. When avalanches had just run, most of the above data were taken in the undisturbed snow just above the fracture line. The centrifugal test for tensile strength was started in December 1966.

General Field Procedure

When a storm was imminent, several snowboards were placed in the avalanche loading zone to aid in dating the new snow. After the storm, resistance to penetration was measured for the entire snow depth near one of the snowboards with a rammsonde (Bader 1954, Niedringhaus 1965). This also established total snow depth, height of snowboard above ground, and a convenient height reference for all subsequent data.

A pit, dug down to the snowboard, exposed a cross section of the new snow. Snow layers were delineated by visual inspection or, in most cases, by inserting a piece of stiff plastic into the pit wall and moving it slowly upward to detect changes in hardness. Snow grain size and type were estimated with the aid of a millimeter grid and hand lens according to the International Classification (International Association of Hydrology 1954). Snow temperature was measured at 10-cm intervals with a thermistor probe and a bridge circuit (Swanson 1962).

Samples were taken in each significant snow layer with the standard SIPRE (USA CRREL) 500 cm ^{3} samplers (189 mm long and 58 mm in diameter). Some samples were taken parallel to the layering for tensile strength tests; others were taken perpendicular to the layers for air permeability. All samples were weighed to determine density.

Small benches were prepared in the pit wall near the center of each snow layer, and shear strength was measured in place by two methods—the torque vane and the shear frame.

Snow crystals were photographed, and air permeability and tensile strength tests were carried out on field samples in an unheated hut near the study site. Temperature in the hut was usually well below freezing.

Physical and Mechanical Properties

Physical and mechanical properties are summarized in the Appendix.[3/] For the most part, the snow was less than 2 weeks old. This new snow averaged 5 days of age when sampled; in a few cases, ages were not known or were in excess of 2 weeks. Where such data are used in this report, they are clearly marked.

Density

This well known and relatively easy-to-measure feature is the most definitive single property of snow. Density of younger samples varied from 40 to 450 kg m^{-3}; it went to 500 kg m^{-3} in a few of the older samples of unknown age.

Density was computed for both perpendicular and horizontal samples. The horizontal samples were usually taken very near the midpoint of the perpendicular samples. A "t" test applied to 67 pairs of density samples showed no significant difference between horizontal and vertical samples:

	Horizontal	Vertical
Average density (kg m^{-3})	254	257
Standard deviation	+0.088	+0.083
Coefficient of variation (percent)	34.8	32.1

Density sampling gave no difficulties except on a few occasions when very tough, older snow was encountered near the bottom of deep pits. In such cases, it often took two men to push the sample tube into the snow, and once or twice the cutting edge of the steel tube was bent by ice layers.

A scatter diagram of density (ρ) versus age (t) showed a general increase in density with age, with the greatest increase in the first 2 to 3 days

[3/] Profiles of all pits were also prepared, but are not included in this report. Copies of the working version of the profiles can be obtained by request.

(fig. 2). It also showed four points (marked +) with unusually high densities for their age, and three others (marked Δ) with densities only about half those expected. This confirmed field observations that some of the young snow layers were unusually hard and dense for their age, while a few of the older layers had remained remarkably soft.

The regression equation is

$$\rho = 161 + 0.139 \log (t)$$

$$r = 0.61$$

The 95 percent continuous confidence interval for this regression based on five density samples for each age, is delineated by dashed lines in figure 2. Samples above the upper confidence limit are called initial hard slab; those below the lower limit are called persistent soft snow. The remainder are called typical aged snow.

There are several things that should be pointed out about the designations just described. First, the statistical approach offers a convenient and somewhat objective way of making the distinctions while still recognizing the continuous nature of the density-age relation. Second, the decision to use the density-age relation rather than strength—age or ram resistance—age was arbitrary, as was the choice of the five-sample continuous confidence interval.

The use of the term **initial hard slab** was an attempt to distinguish snow that develops high density and strength in the first few days from that which has had several weeks or a month to toughen. The current definition of hard slab is based solely on the degree of cohesion as reflected in the shape of blocks in the avalanche debris, and does not distinguish between 1.5- to 2-day-old initial hard slab and aged snow 2 to 4 weeks old. Typical aged snow and persistent soft snow would be called soft slab by the average field man.

Table 1 was prepared to see how well the concept of **initial hard slab** based on density-age relations compared to the type of avalanches actually observed. Most of the avalanches within a 5-mile radius of the study area that ran on the 3 days

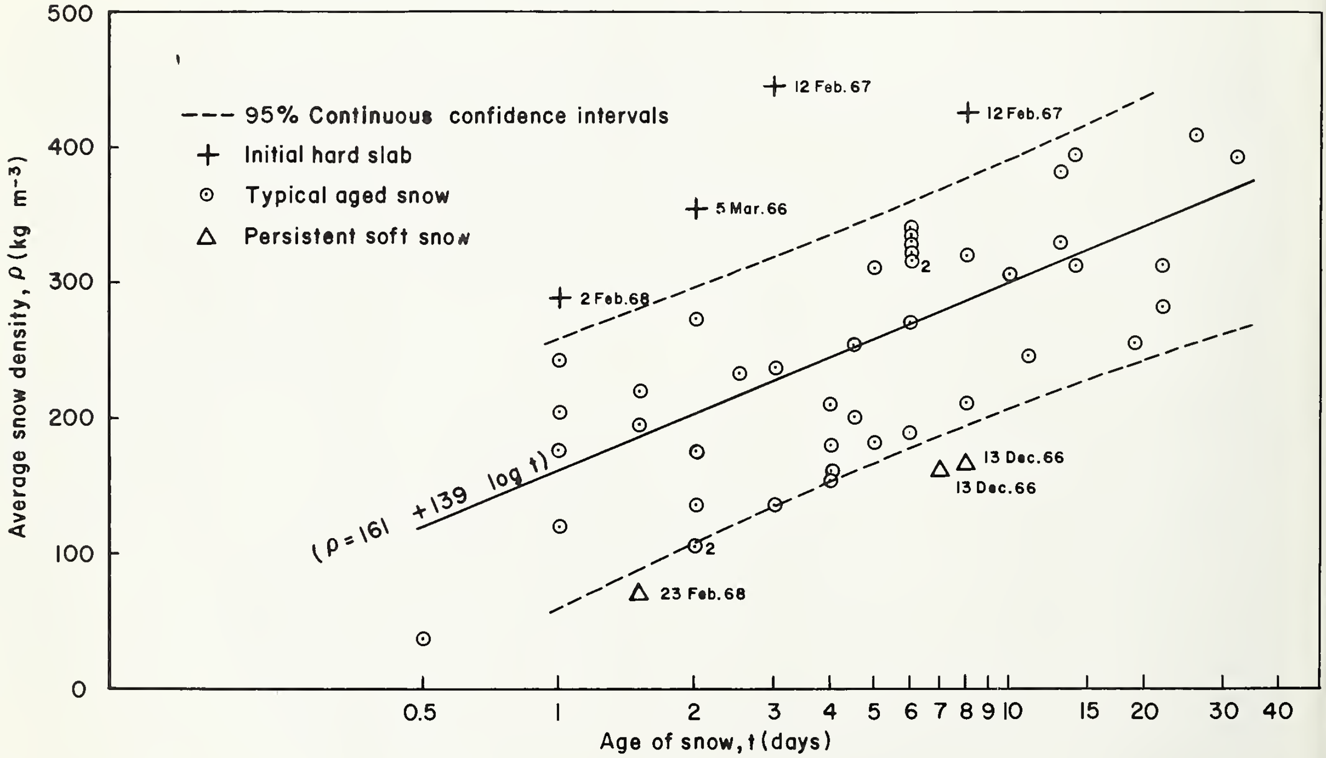


Figure 2.--Density (ρ) as a function of age (t). Points are the average of two to four density samples. Numbers indicate places where one symbol represents two points. Continuous confidence intervals (95 percent) are for the means of five samples for each age.

when initial hard slab was observed in the study pits (March 5, 1966, February 12, 1967, and February 2, 1968) were hard slab avalanches. On all other study days, except February 3-4, 1965, soft slab avalanches predominated. There is no way to be sure if the hard slab avalanches of February 3-4, 1965 were from initial hard slab or from older snow, because the snow at the study site in the Lift Gully could not be aged accurately. It was impossible to determine in the field if the hard slab avalanche that ran down the Lift Gully on February 2, 1965 started above or below the fracture line of the soft slab avalanche that had run in the same area on January 28, 1965. If the February avalanche started downhill of the January fracture line, the February snow would have been about 3 days old and would have been designated initial hard slab. Since we couldn't be sure of this, however, it seemed more likely the snow involved in the February avalanche was at least 6 days old, and should be called typical aged snow.

A more general, season-long comparison of the frequency of initial hard slab and the occurrence of hard slab avalanches can be made from table 2. For the 3-year study period, 1965-68, initial hard slab was found in 15 percent of the pits. Yet on a dozen or more avalanche paths immediately adjacent to the study site, about one-fourth of the natural and between 30 and 40 percent of the artificially released avalanches were of the hard slab variety. For the 18-year period, 1950-68, the proportion of hard slab avalanches in the grand total was 30 percent, or about double the frequency of initial hard slab conditions observed during the study. This is probably due to the high proportion of artificially released avalanches which, because of the relatively severe trigger, often involve layers of older snow.

Table 1.--Type of snow found in snow pits and type of avalanches observed within 5 miles of the study site on or near date pit was dug

Pit date	Type of snow in pit	Type of avalanches: Soft slab	Hard slab	Loose	Avalanche date
		- - Number - - -			
1965					
28-29 Jan	Typical aged	4	0	0	28 Jan
		6	1	1	29 Jan
3-4 Feb	Typical aged	1	4	0	2 Feb
		0	2	0	3 Feb
15-16 Mar	Typical aged	1	0	0	13 Mar
		4	1	0	14 Mar
		3	0	0	15 Mar
1966					
5 Mar	Initial hard slab	0	1	0	4 Mar
		0	2	0	5 Mar
7 Dec	Persistent soft	2	0	0	7 Dec
		5	0	0	9 Dec
13 Dec	Persistent soft	0	0	0	
1967					
3-4 Jan	Typical aged	2	0	0	3 Jan
		4	0	0	4 Jan
6 Jan	Typical aged	1	0	0	6 Jan
		1	0	0	7 Jan
15 Jan	Typical aged	3	0	0	14 Jan
		5	0	0	15 Jan
		2	0	0	16 Jan
31 Jan	Typical aged	0	0	0	
1 Feb	Typical aged	0	0	3	1 Feb
12 Feb	Initial hard slab	2	3	0	11 Feb
		1	0	0	13 Feb
7-8 Dec	Typical aged	4	1	0	7 Dec
		3	0	0	9 Dec
21 Dec	Typical aged	1	0	0	21 Dec
		3	0	0	22 Dec
1968					
17-19 Jan	Typical aged	2	0	0	13 Jan
2 Feb	Initial hard slab	1	0	0	1 Feb
		0	1	0	3 Feb
20 Feb	Typical aged	4	0	0	20 Feb
23 Feb	Persistent soft	1	0	0	22 Feb
		8	0	0	23 Feb
		6	0	0	24 Feb
29-30 Apr	Typical aged	0	0	3	30 Apr
Total		80	16	7	

Table 2.--Slab avalanches in or near the Berthoud Pass study area

Date and type of release	Type of avalanche: Soft slab		Hard slab		Total avalanches	
	No.	Pct.	No.	Pct.	No.	Pct.
1950-68:						
Natural	66	77	20	23	86	19
Artificial	255	68	120	32	375	81
Total or average	321	70	140	30	461	100
1965-68:						
Natural	30	71	12	29	42	30
Artificial	59	60	40	40	99	70
Total or average	89	63	52	37	141	100

If there is any justification in calling the Central Rocky Mountains "the home of the hard slab avalanche," it is not just because of initial hard slab, but also because, in this area of low to moderate snowfall, vigorous explosive control and natural triggers often released older snow layers that have had time to harden and toughen in place.

Grain Size and Type

The snow in the various layers was classified in the field as new snow (type a), settled powder or felted snow (type b), fine-grained old snow (type d), or a mixture of the last two types (fig. 3) (International Association of Hydrology 1954). Experienced

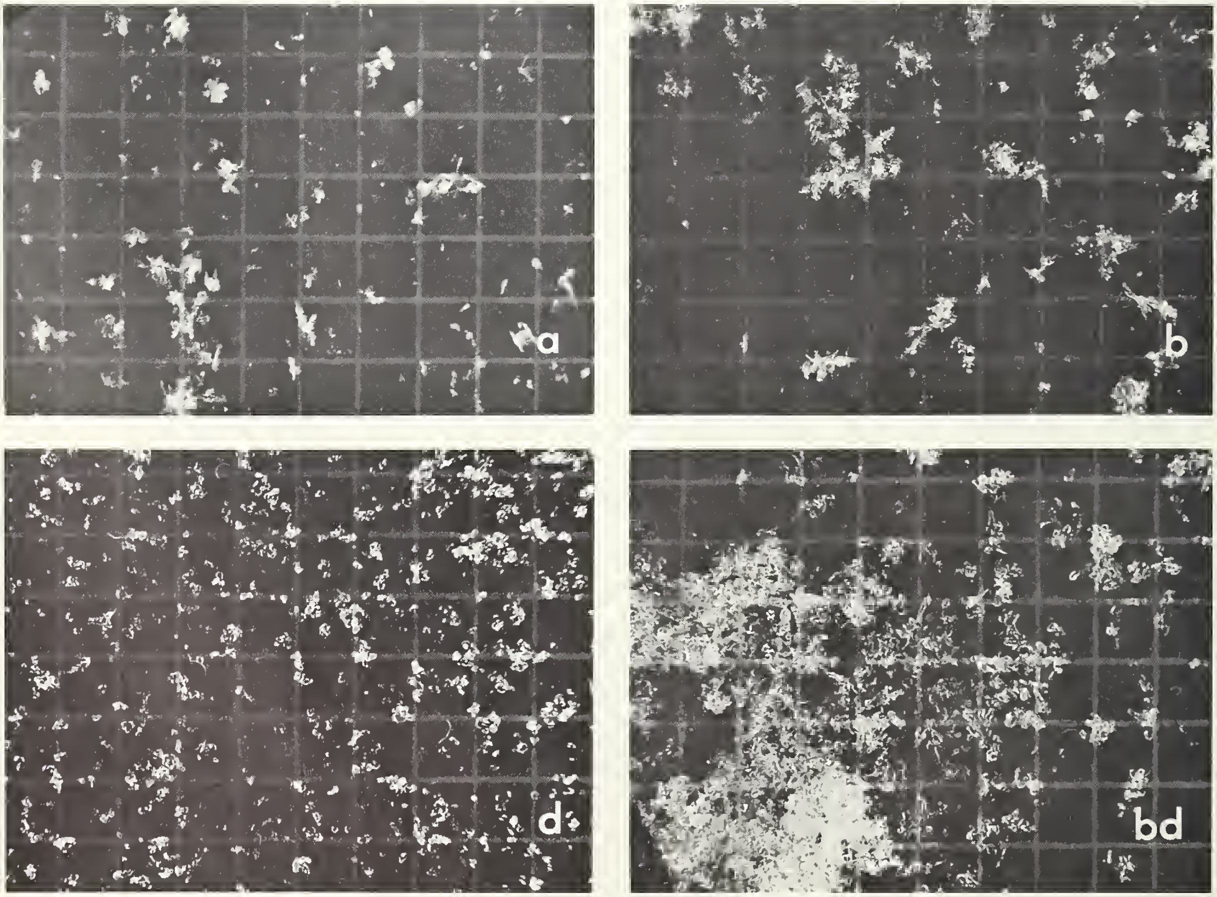
Figure 3.--Snow grain type and size illustrated by pictures from crystal camera (see fig. 5). Grid in background is 2 mm.

Grain type: a
Size: 1 mm
Age: falling snow
Depth: at surface
Density: unknown
Ram resistance: unknown
Tensile strength: unknown
Date: 20 Feb 68

Grain type: b
Size: 1 mm
Age: 1 - 1.5 days
Depth: 28 cm
Density: 68 kg m^{-3}
Ram resistance: 1 kg
Tensile strength: 4.78 gf cm^{-2}
Date: 23 Feb 68

Grain type: d
Size: 0.5 mm
Age: 13 days
Depth: 83 cm
Density: 326 kg m^{-3}
Ram resistance: 48 kg
Tensile strength: 860 gf cm^{-2}
Date: 31 Jan 67

Grain type: bd
Size: 1.5 mm
Age: 4 days
Depth: 15 cm
Density: 222 kg m^{-3}
Ram resistance: 1 kg
Tensile strength: 118 gf cm^{-2}
Date: 30 Apr 68



observers were consistent in their identification of snow type, although we suspected that, rather than relying completely on the physical appearance of the grains, they were subconsciously integrating into their determinations such things as past weather, depth within the pack, relative age, hardness, and density.

As expected, fine-grained old snow (type d) had greater strength, density, and hardness than felted snow (type b). The bd mixture was intermediate in these features. Initial hard slab was fine grained and had high strength and hardness at an early age (fig. 4).

Most of the snow grains were between 0.4 and 0.7 mm in diameter. The new snow tended to be larger grained, especially when it fell with little or no wind. The nature of the study did not require sampling the coarse-grained lower layers, where more active metamorphism had been in progress longer. Grain size in these lower layers, however, is known to range from 1 to 3 mm with a few grains in favorable situations as large as 5 to 7 mm.

Snow grains from the tensile strength samples were photographed in the cold room with a 35 mm camera equipped with extension tubes and an electronic flash (fig. 5). This procedure was fast and gave a life-size image on the negative which could be enlarged many times by standard darkroom techniques for detailed subsequent examination. Examination of many such pictures indicated that a better classification scheme was needed for snow on the ground. Since the completion of this study, such a classification based on the physical processes causing the change and on modern crystallographic concepts has been published by Sommerfeld and LaChapelle (1970).

Figure 4.--Snow grains from initial hard slab. Density 448 kgm^{-3}; age 3 days; tensile strength 635 gf cm^{-2}; ram resistance 100 kg. Background grid 2 mm.

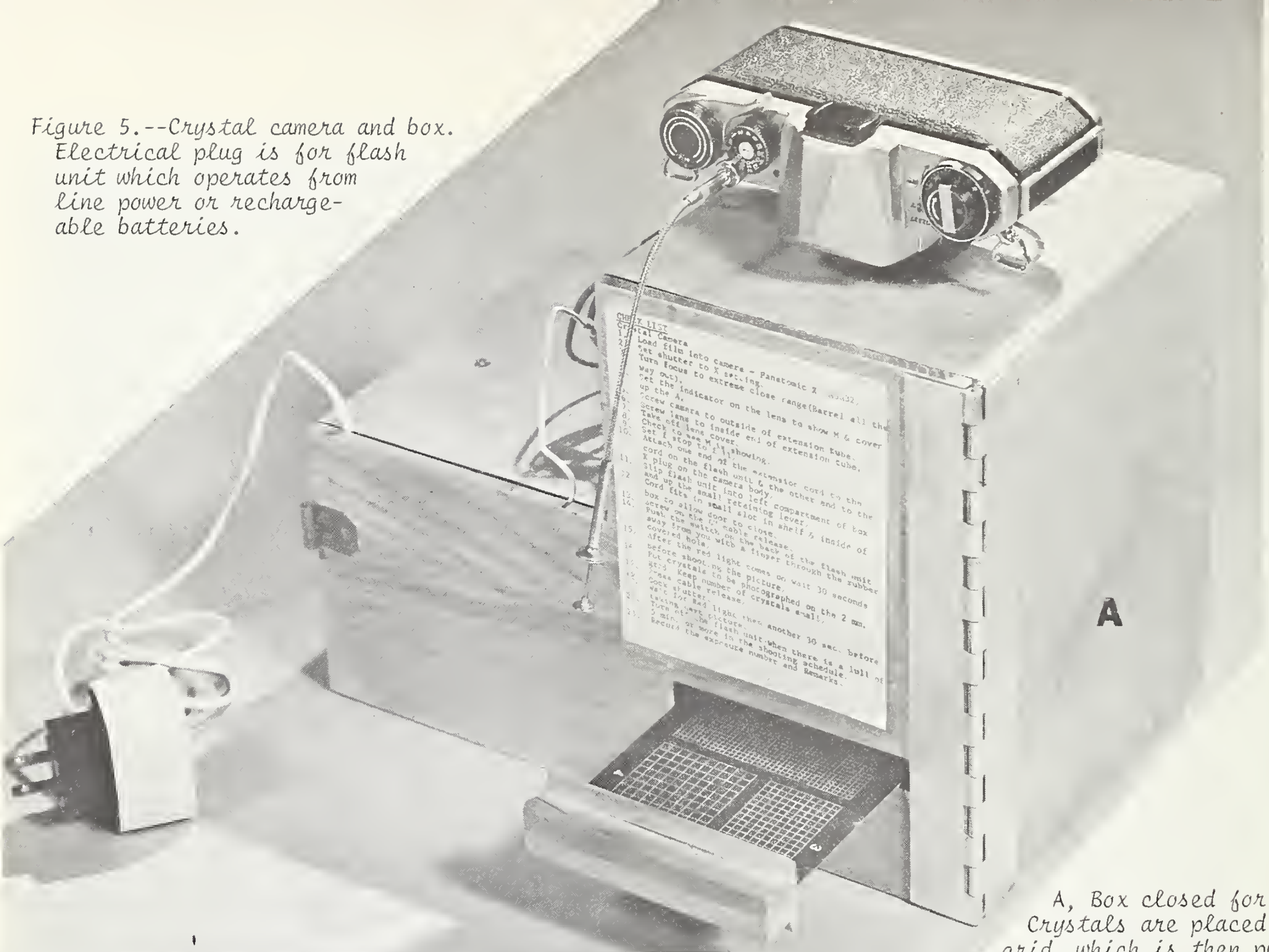
Strength

Fresh snow is usually so soft and poorly bonded, and so subject to changes with temperatures and time, that classic strength tests such as unconfined compression and simple tensile are difficult to perform. In their place, a series of field and laboratory tests have been devised that at least give indexes of strength (Bader et al. 1951, de Quervain 1951, Perla 1969).

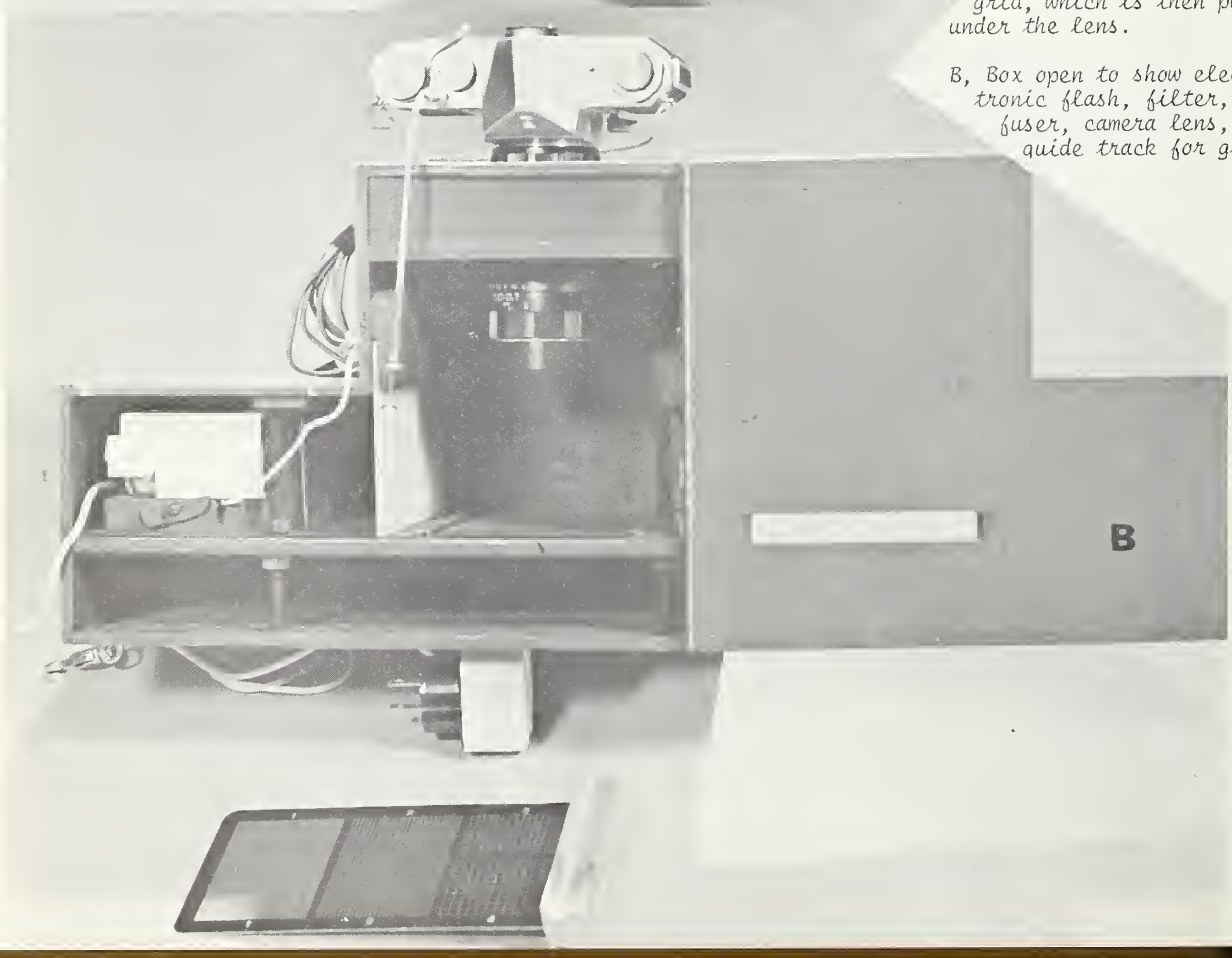
The centrifugal or spin tester illustrated in figure 6 was used to measure tensile strength. A cylindrical sample of snow was taken parallel to the layering in a 500 cm^3 sample tube. The field sample was then taken to an unheated hut and transferred to a similar tube mounted on top of the tester by placing the two tubes end to end and pushing the snow from one to the other with a wooden ram. Care was needed in transferring samples of very porous snow, but samples with densities as low as 40 kg m^{-3} were successfully tested. A yoke that fits into grooves in the tube restrained the sample in the middle and reduced its cross-sectional area. The sample was then spun horizontally, by means of a variable-speed electric motor. Speed was increased two to three revolutions per second, or about 50 to 75 gf cm^{-2} sec^{-1} for a sample of 250 kg m^{-3} density.[4]

[4] Grams force is abbreviated as gf in this paper. 1 gf = .0098 Newton

Figure 5.--Crystal camera and box. Electrical plug is for flash unit which operates from line power or rechargeable batteries.



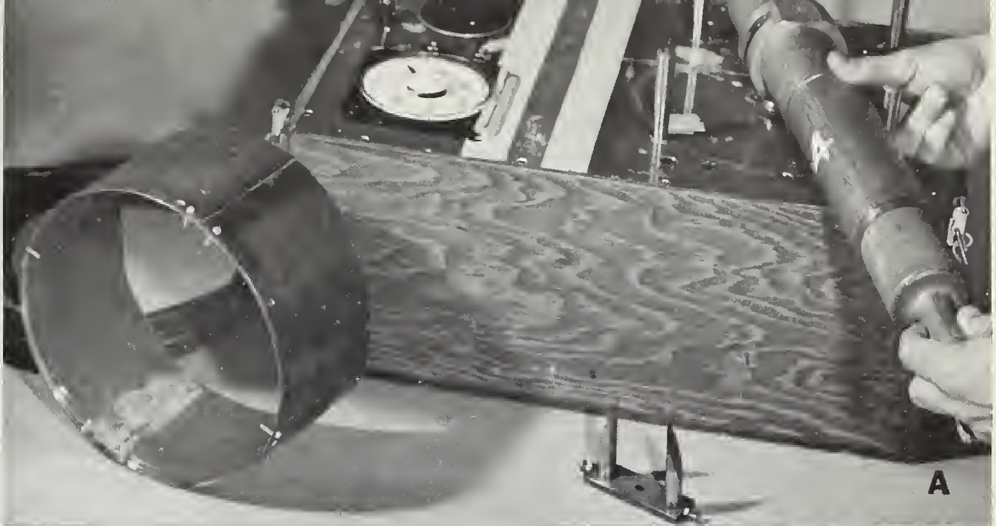
A, Box closed for use. Crystals are placed on grid, which is then pushed under the lens.

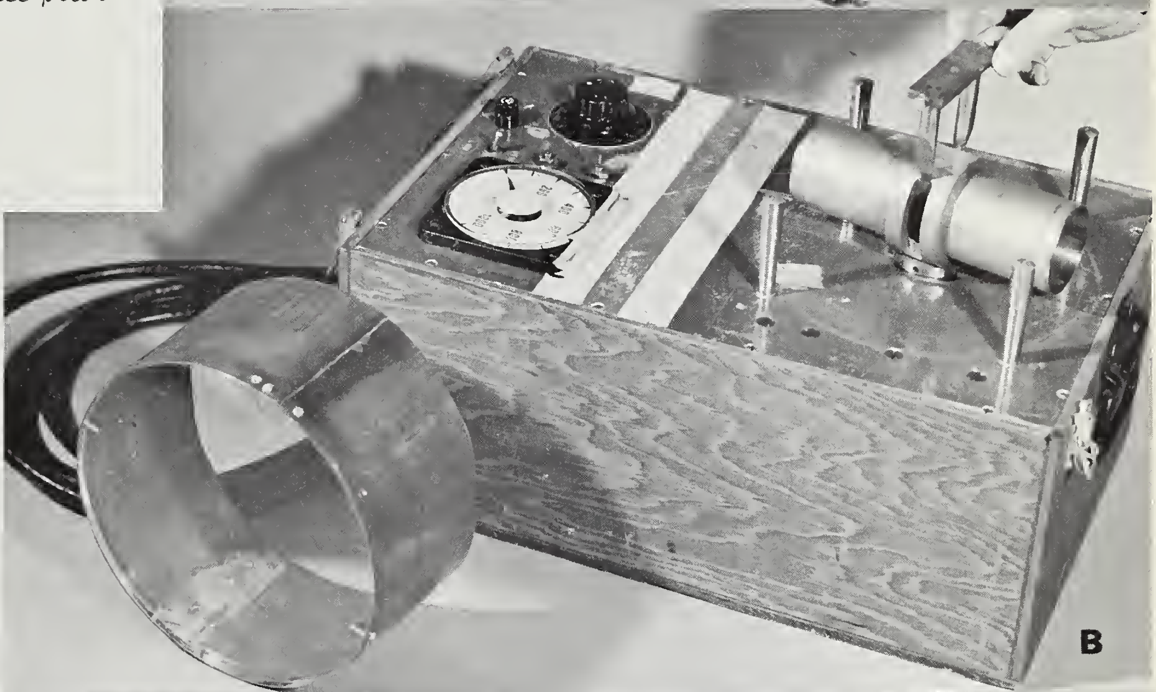


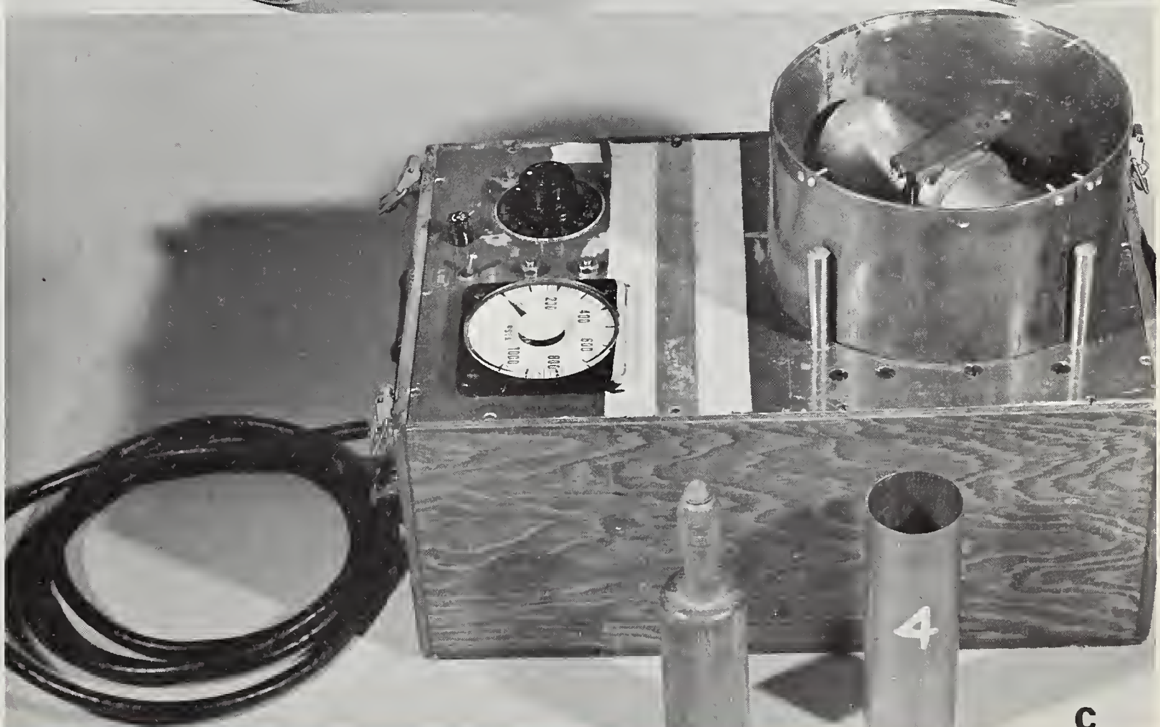
B, Box open to show electronic flash, filter, diffuser, camera lens, and guide track for grid.

Figure 6.--Centrifugal or spin tester used to measure tensile strength:

A, Transferring sample from tube to tester;
B, Placing restraining yoke in position;
C, Shield in place prior to test.







Strength was computed from the angular momentum at the time of failure (Bader et al. 1951, p. 11). The sample usually failed in the middle where the cross-sectional area was reduced by the restraining yoke. On a few occasions, however, there were flaws in the sample that caused failure near one end. In these cases, the data were not used. In general, this test offered relatively few problems—most of which were easy to detect—and the results were felt to be the best of the several strength tests.

Tensile strength of snow 14 days old, or younger, as measured with the spin tester, varied from 1.0 to 1712 gf cm^{-2}. The maximum value was 2100 gf cm^{-2} for a 26-day-old sample measured on January 18, 1968. Strength increased rapidly with density (fig. 7), but a fourfold range of strength for a given density was common.

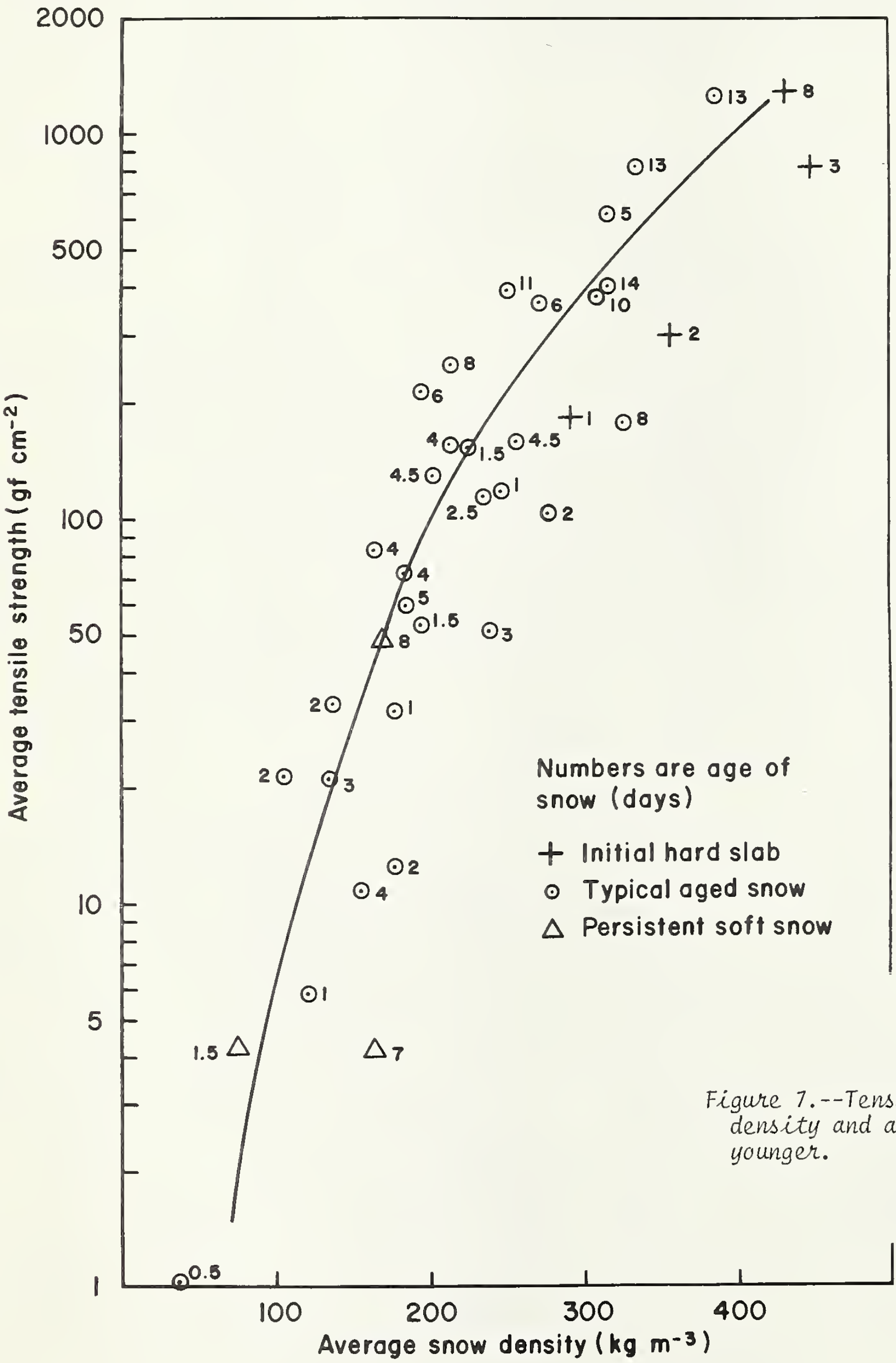


Figure 7.--Tensile strength as a function of density and age for snow 14 days old or younger.

There was a tendency for the younger snow of a given density to be weaker than the older snow of the same density, especially for densities of 200 kg m^{-3} and higher. Initial hard slab shows up in figure 7 as relatively weak, young snow of high density. For example, our data indicate snow with a density of 350 kg m^{-3} should have a tensile strength of 600 to 700 gf cm^{-2} rather than the 300 gf cm^{-2} strength measured on March 5, 1966 in 2-day-old initial hard slab.

The slopes of the regressions of tensile strength versus density appear the same for these data and those of de Quervain (1951), Roch (1966), Keeler and Weeks (1967), and Keeler (1968) (fig. 8). There is some displacement of the regressions, however, with the old, fine-grained snow of Keeler and Weeks (1967) being the strongest, and the fresh, fine-grained snow of Roch (1966) being the weakest for a given density.

In a series of controlled-temperature experiments, Roch (1966) showed an increase of tensile strength with a decrease in temperature. This amounted to about doubling the strength as temperature dropped from -2° to -40° C. Although no such trend could be detected in our field samples, which were mostly between -5° and -15° C., this should not be construed as contradictory evidence because our study was not designed to relate strength to temperature.

Two indexes of shear strength were measured. In the torque vane test, a cross-shaped vane was pushed from above to the desired depth in the snow and turned with a torque wrench (Mellor 1969, Radforth and Rush 1964, p. 17). This type of in situ test is widely used in soils work where it has proven to be well correlated with laboratory tests of strength (Hamilton 1959).

Torque vane shear strength was computed on the basis of the cylinder generated by the rotation of the vane. Although this was the fastest and easiest of the strength indexes to measure in the field, the tendency for the snow to fail in a "stick-slip" manner caused difficulties. Apparently what happens is that the snow just ahead of the vanes compacts when force is first applied, causing initial failure. As more force is applied, the cylinder of disturbed snow breaks free of its surroundings in ultimate failure. For our purposes, the force needed to cause ultimate failure was used to determine what we call torque vane strength. This value corresponds to the strongest snow in a layer as thick as the vane is long. For all but the toughest snow, we used a vane 3 inches long by 1.5 inches wide. In tough snow, a smaller vane, 2 x 1 inch, was used. Neither was satisfactory for new snow when densities were 100 kg m^{-3} or less. The torque vane was loaded at a rate of about 30° per second, and failure usually occurred in the first 1 to 1.5 seconds.

The correlation between tensile and torque vane strengths is good (fig. 9). The general trend, however, is much closer to 1:1 than it is to the 10:1 ratio found by Keeler and Weeks (1968).

The plot of torque vane strength as a function of age shows too much scatter to be helpful.

The second index of shear strength was determined with a spring balance and a small metal frame, 100 cm^2 in area, which was slightly broader in front than back (de Quervain 1951, Mellor 1969). The frame was pushed into the snow from above. Snow in front of it was cleared away, and the spring balance, attached to a hook on the frame, was pulled with a steady motion parallel to the top and bottom planes of the frame. This technique gave best results when the bottom of the frame was at the center of a uniform layer of weak snow, or at the boundary between two distinct layers. In the first case, the strength of the layer was measured; in the second, the strength of the bond between layers. Most of the readings reported here were made in the middle of layers rather than at layer boundaries. Data from this device are referred to hereafter as shear frame strengths.

Several difficulties were encountered while using the shear frame. In cases where a tough snow layer lay on top of a softer one, it was necessary to cut the tough snow with a knife and insert the frame in the cuts to avoid collapsing the softer layer or shattering the tough, brittle layer when inserting the frame. This procedure was also necessary for soft feltlike snow, which deforms under the weight of the frame. In other cases, deep, uniform layers of tough snow often fail along a curved rather than a plane surface.

Shear frame strength was appreciably less than any other strength index. This may, in part, reflect the tendency for some snows to fracture when the frame is inserted unless knife cuts are made. Keeler and Weeks (1967) found torque vane and shear frame strengths to be equal. We found them to be equal only for very weak snow (<10 gf cm^{-2}, fig. 10); at higher strengths, torque vane strengths were 3 to 4 times shear frame strengths.

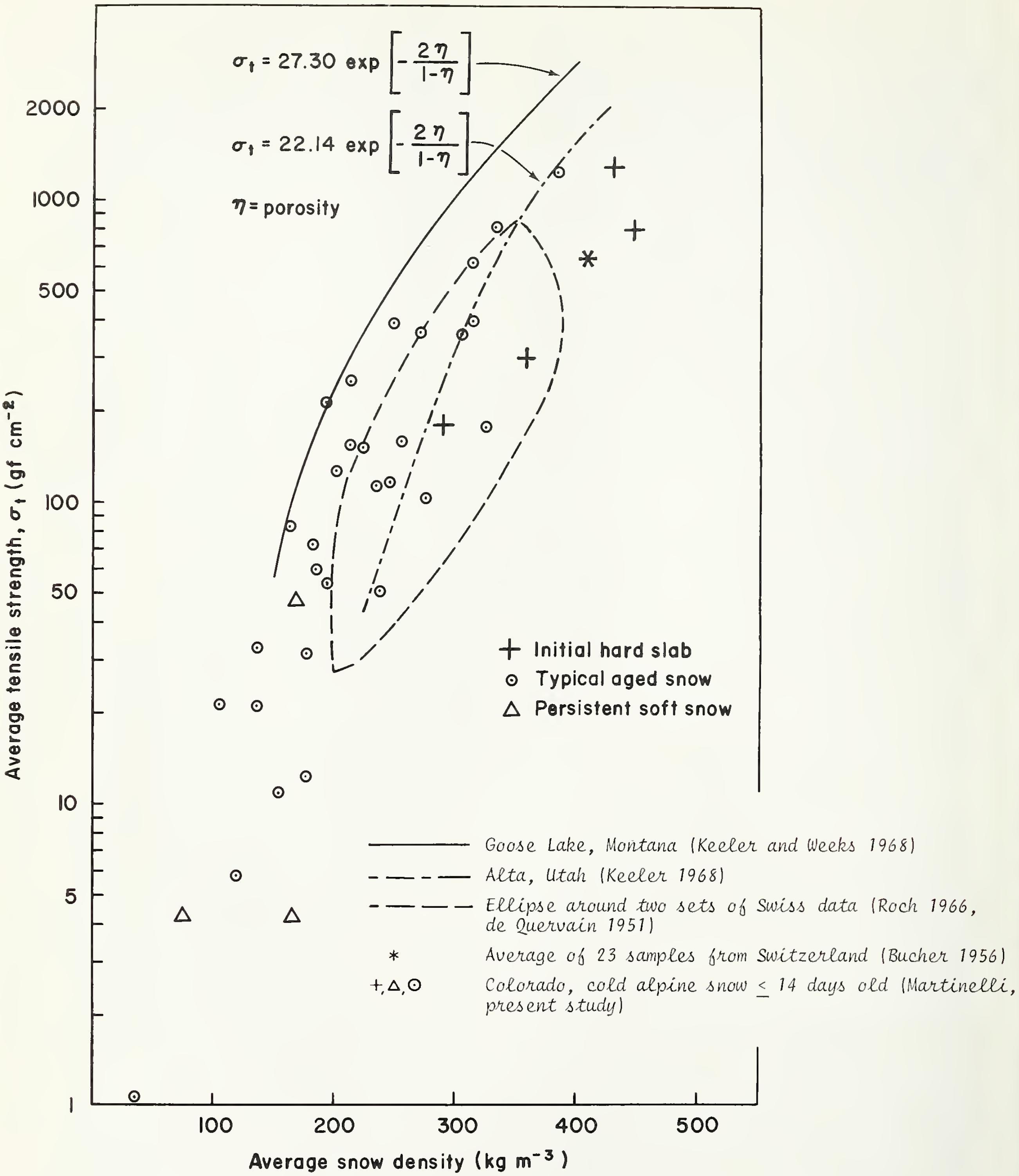


Figure 8.--Average tensile strength as measured by spin tester versus density.

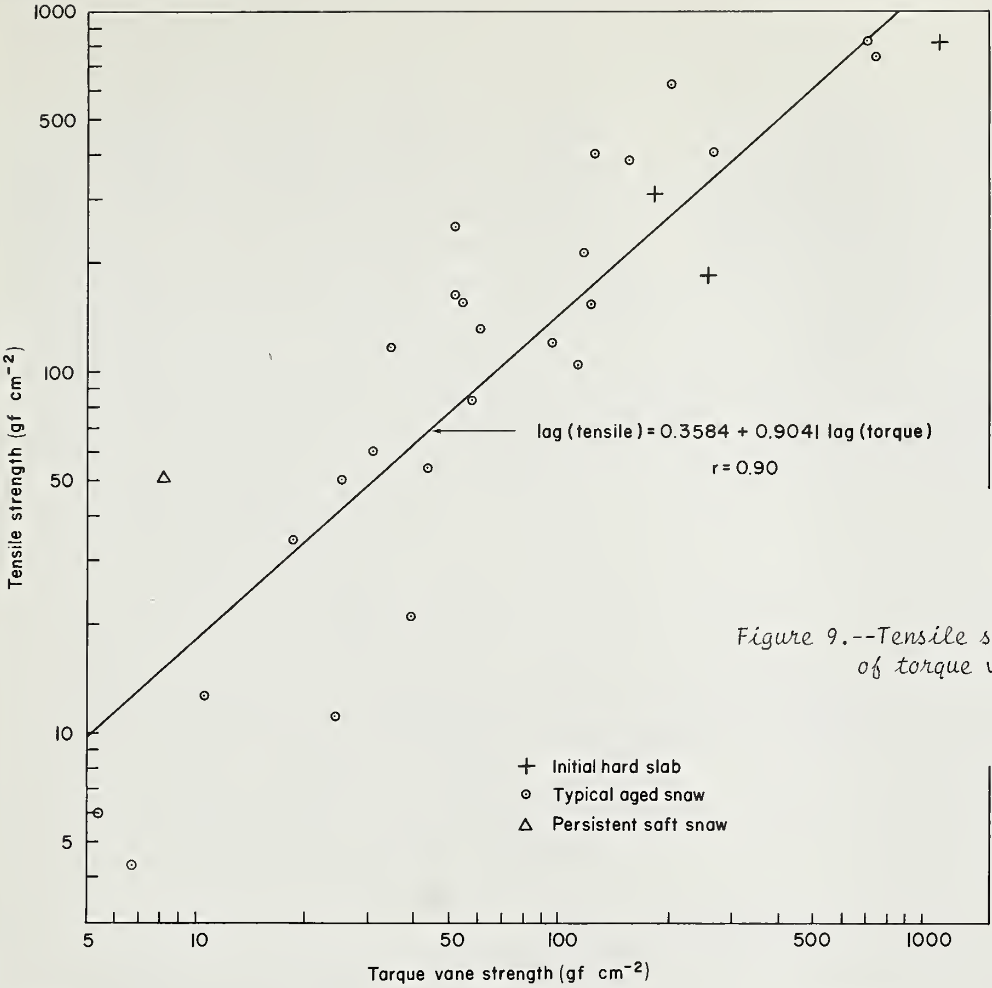


Figure 9.--Tensile strength as a function of torque vane strength.

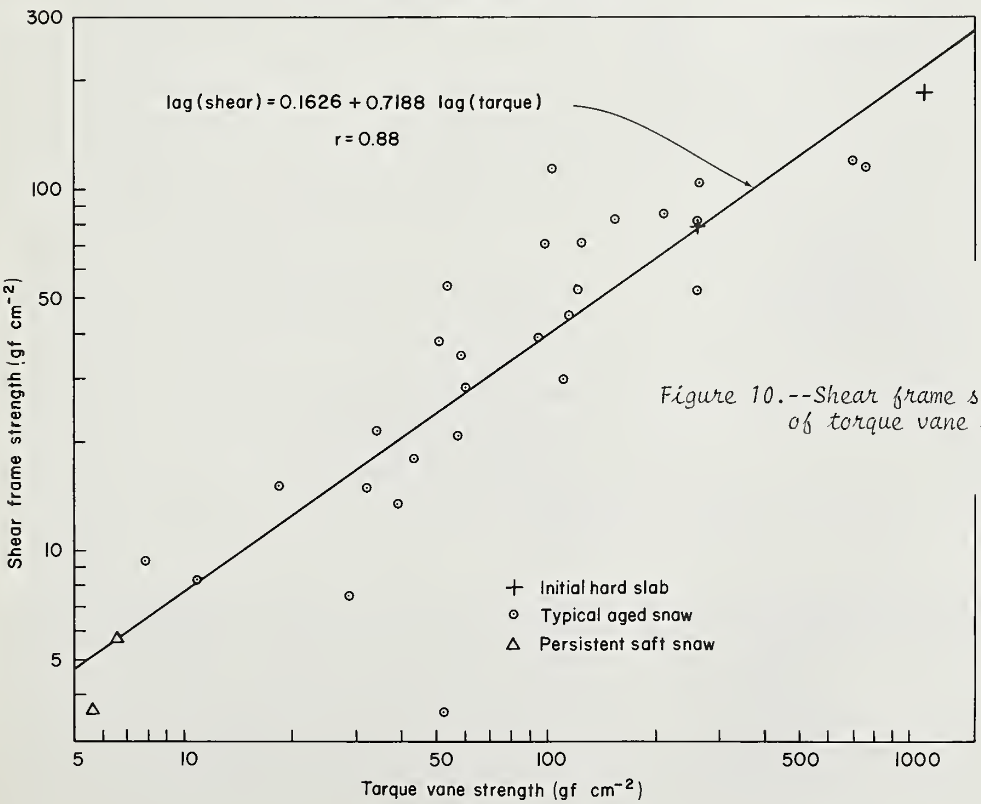


Figure 10.--Shear frame strength as a function of torque vane strength.

The regression between tensile and shear frame strengths (fig. 11) seems to have a time or age dependency (fig. 12). For example, tensile strength is about three times shear frame strength for snow 2 to 3 days old, but it is 5.5 to 6 times shear frame strength for snow 10 days old. There is also a variation with the strength of the snow. Tensile strength is 5 or 6 times shear strength for strong snow, but less than twice shear frame strength for weak snow (fig. 13).

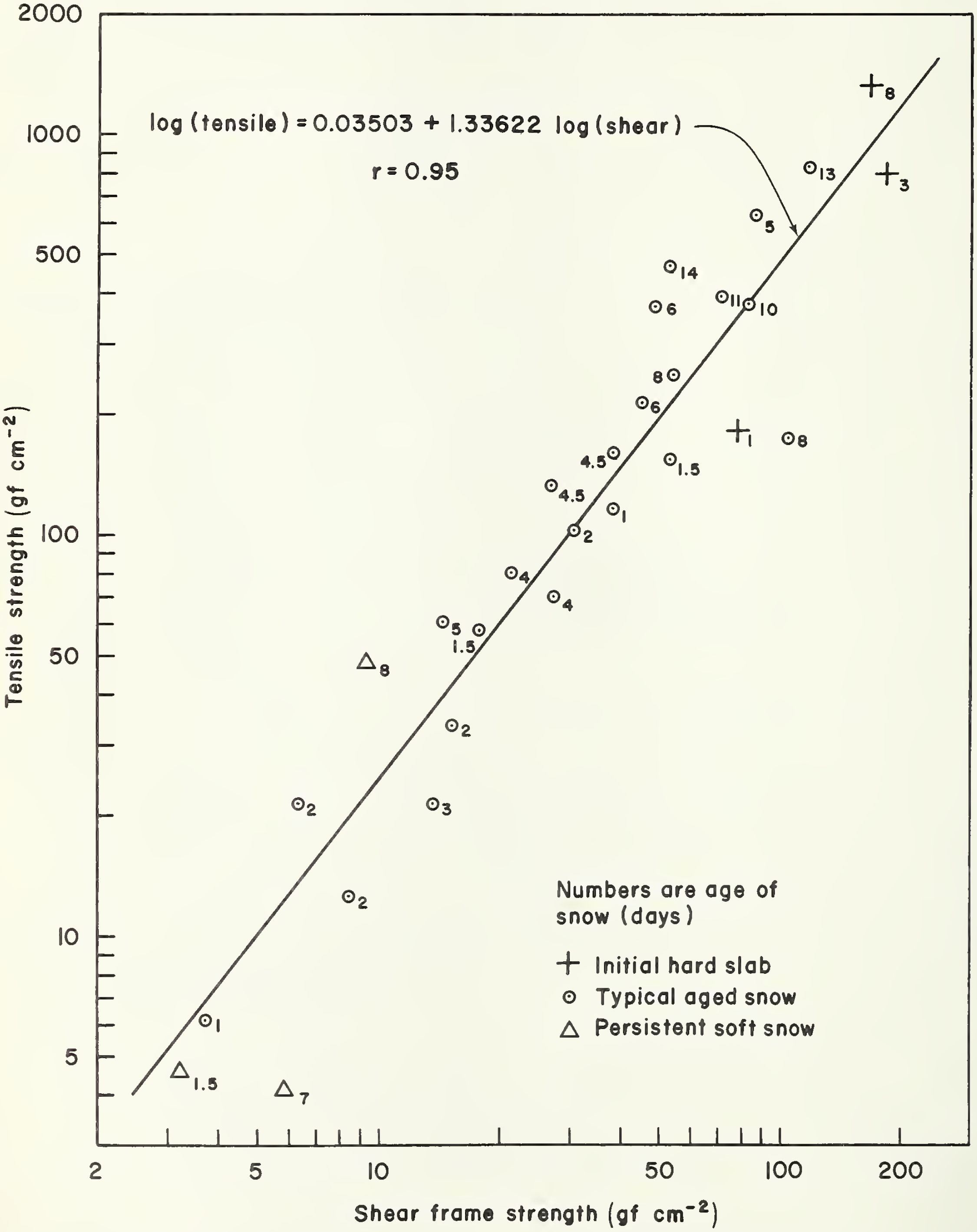


Figure 11.--Tensile strength as a function of shear frame strength.

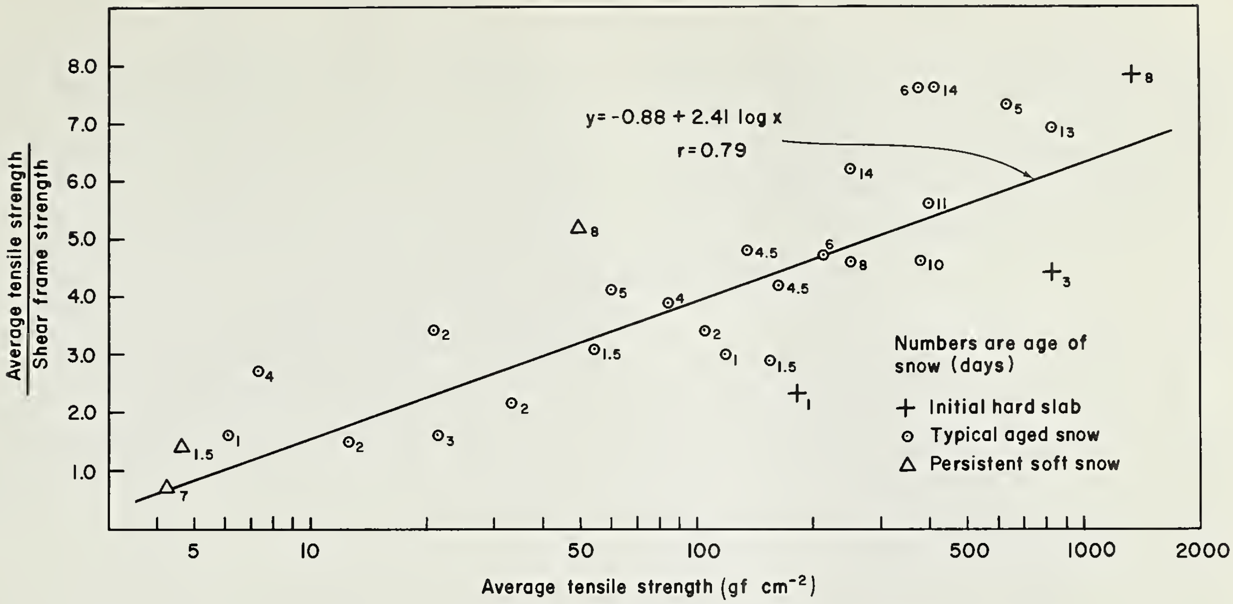


Figure 12.--Average tensile strength/shear frame strength as a function of age. Dates are given for a few points to facilitate reference to the appendix.

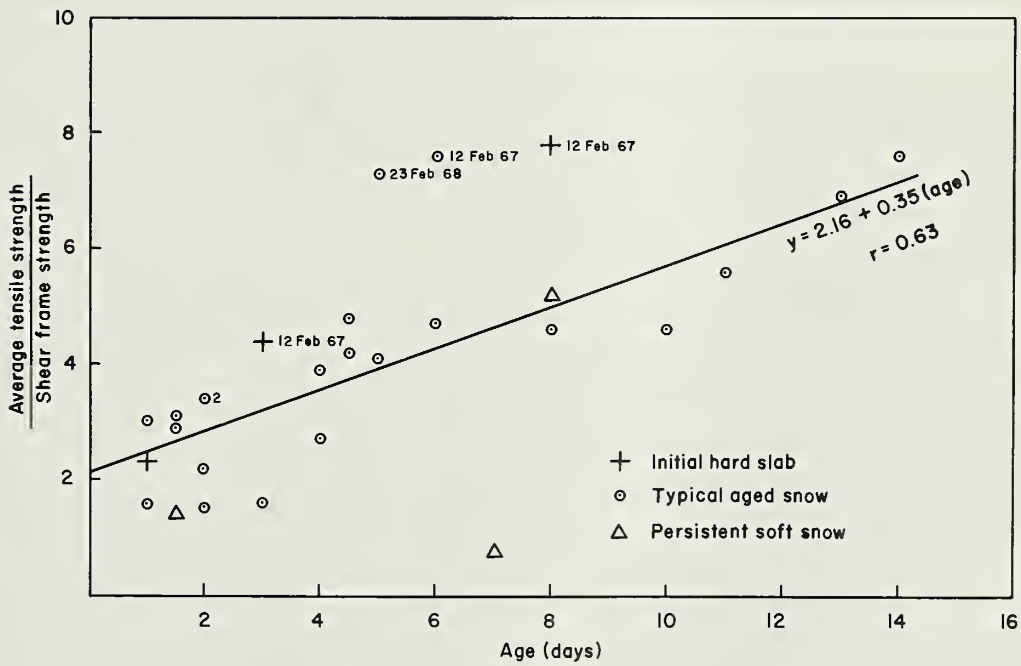


Figure 13.--Average tensile strength/shear frame strength as a function of average tensile strength.

Roch (1966) also showed that the relationship between shear and tensile strengths (as measured by the shear frame and spin tester) varies greatly for strong and weak layers. He reported tensile strength to be about 5 times shear strength in strong layers, but no greater than twice shear strength for weak layers. Keeler (1968), on the other hand, reported tensile strength to be 6 to 6.5 times shear strength for snow at Alta, Utah, and Goose Lake, Montana, without qualifications or reservations.

All strength measures showed the expected increase as grain type changed from settled powder (type b) to fine-grained old snow (type d). There

was also a rapid increase in all strengths as density increased. The apparent increase in strength with age may be only a reflection of the strong dependency between density and age, but it is more likely to be a function of the number and strength of the grain-to-grain bonds.

Ram Resistance

The technique for determining the hardness profile of a snow cover with an impact penetrometer was first described by Haefeli (1954), and has been widely used since (Mellor 1969). A sectional rod with a 60° conical tip, 4 cm in diameter, is driven into the snow by a falling weight. Ram resistance is one of the easiest snow properties to measure in the field because no pit is needed. Data presented here were computed from the equation:

$$R = \frac{w_1 h x}{\Delta E} + w_2$$

where

R = ram resistance (kg)
w_2 = total weight of hammer plus penetrometer (kg)
w_1 = weight of hammer (kg)
h = height from which hammer is dropped (cm)
x = number of drops
ΔE = penetration of point for x blows (cm)

No correction was made for the energy of impact or coefficient of restitution as mentioned by Haefeli (1954, p. 128) and Waterhouse (1966). Although these corrections may be appreciable under certain conditions, they have usually been ignored; hence uncorrected data are easier to compare with those already published.

Ram resistance and density were available not only from the alpine study site (called the Roll), but also from a nearby small opening in the timber (called Q-12 Park).

A least squares fit of the form

$$\log R = a + b\hat{\rho}$$

where

R = ram resistance in kg
$\hat{\rho}$ = density in kg m^{-3}

was computed for both sets of data excluding depth hoar, isothermal snow, and ram numbers of 1. The results confirm the positive correlation between ram number and density (fig. 14) previously reported for polar snow by Bull (1956) and for seasonal snows by Keeler and Weeks (1967, 1968). Table 3 shows a reasonably good agreement for all the data except that from Q-12 Park. Density is not so well correlated with ram number at Q-12 Park as at the other sites, nor does the ram resistance increase as much per unit increase in density. The lower strength at Q-12 Park is attributed to protection from the wind. All the other sites in table 3 were considerably more exposed than Q-12 Park.

For prediction of density, the regression for the 14-day and younger cold snow from the Roll would be

$$\hat{\rho} = 131.0 + 130 \log R,$$

that for cold snow no more than 1 month old from the sheltered Q-12 Park would be

$$\hat{\rho} = 209 + 86 \log R,$$

and for cold snow in Q-12 Park no more than 4 months old, it would be

$$\hat{\rho} = 213 + 108 \log R$$

A covariance analysis of the Roll (112 points) and the 1 month and younger data from Q-12 Park (64 points) indicated the intercepts were significantly different at the 1 percent level, and the regression coefficients were significantly different at the 5 but not at the 1 percent level.

This analysis also showed that, for a given ram resistance, alpine snow had a lower density than snow from a sheltered opening, especially for ram numbers below about 15 kg. Thus alpine snow appears to be stronger for a given density than snow from a sheltered opening—provided one accepts ram resistance as an index of strength.

Although the exact relationship between strength and ram resistance is not known (de Quervain 1951), figure 15 illustrates the good correlation between ram resistance and tensile strength. This relation can be improved by making allowances for the age of the snow. For ram resistance between 5 and 30 kg, the tensile strength of snow 4 days old and older is 1.5 times that of younger snow with the same ram resistance.

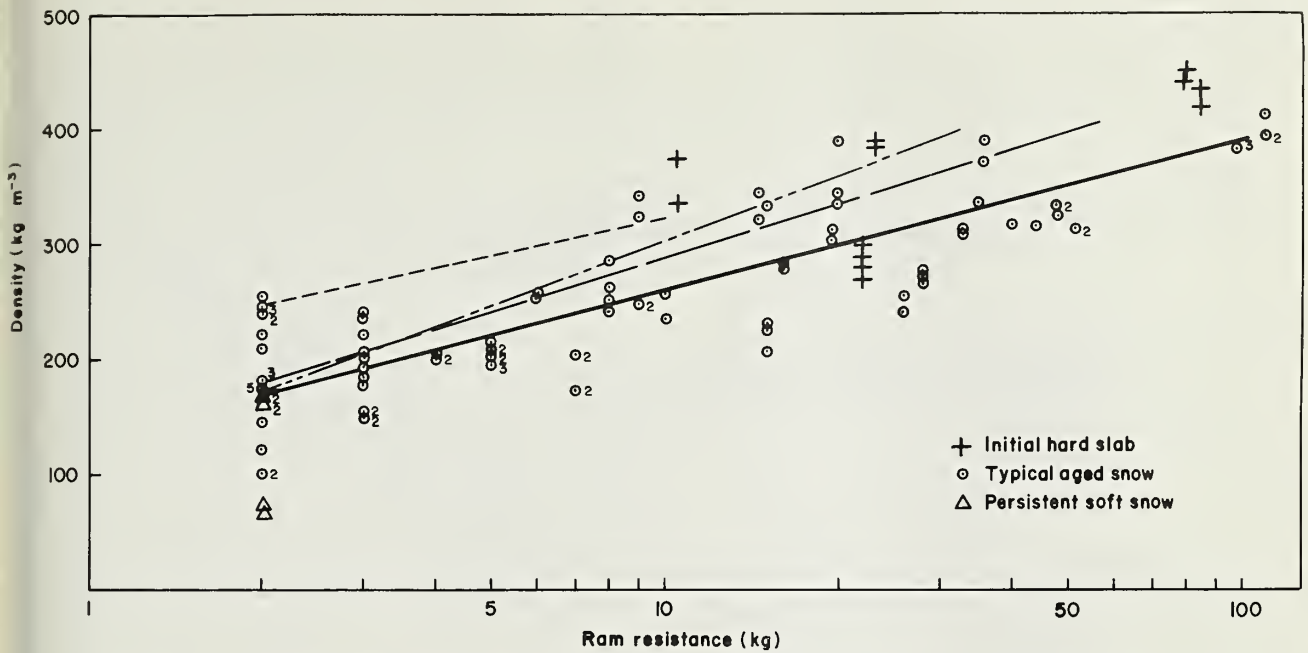


Figure 14.--Density as a function of ram resistance. All data points are for this study. Numbers indicate symbols that represent more than one point.

— — — — Greenland snow (Bull 1956)

——— — — — Goose Lake, Montana, dry snow (Keeler and Weeks 1968)

——— ——— Q-12 Park, near study site. Cold snow; all ages; depth hoar and ram resistance of 1 kg excluded.

——— +, △, ⊙ } Cold alpine snow ≤ 14 days old (Martinelli, present study)

Table 3.--Summary of regression and correlation coefficients for several sets of data fitted to the regression

$$\log R = a + b\hat{\rho}$$

Source	a	b	Correlation coefficient (r)	Age of snow	Density range
					$kg\ m^{-3}$
Bull (1956)	-0.6107	0.00531	0.80		
Keeler & Weeks (1967)	- .8446	.00640	.94	<4 months	100 - 510
Keeler (1968)	- .7482	.00599	.89	<4 months	150 - 430
This Study:					
Roll	- .428	.00543	.84	≤14 days	40 - 450
Q-12 Park	- .305	.00343	.54	≤1 month	100 - 390
Q-12 Park	- .463	.00421	.68	≤4 months	100 - 430

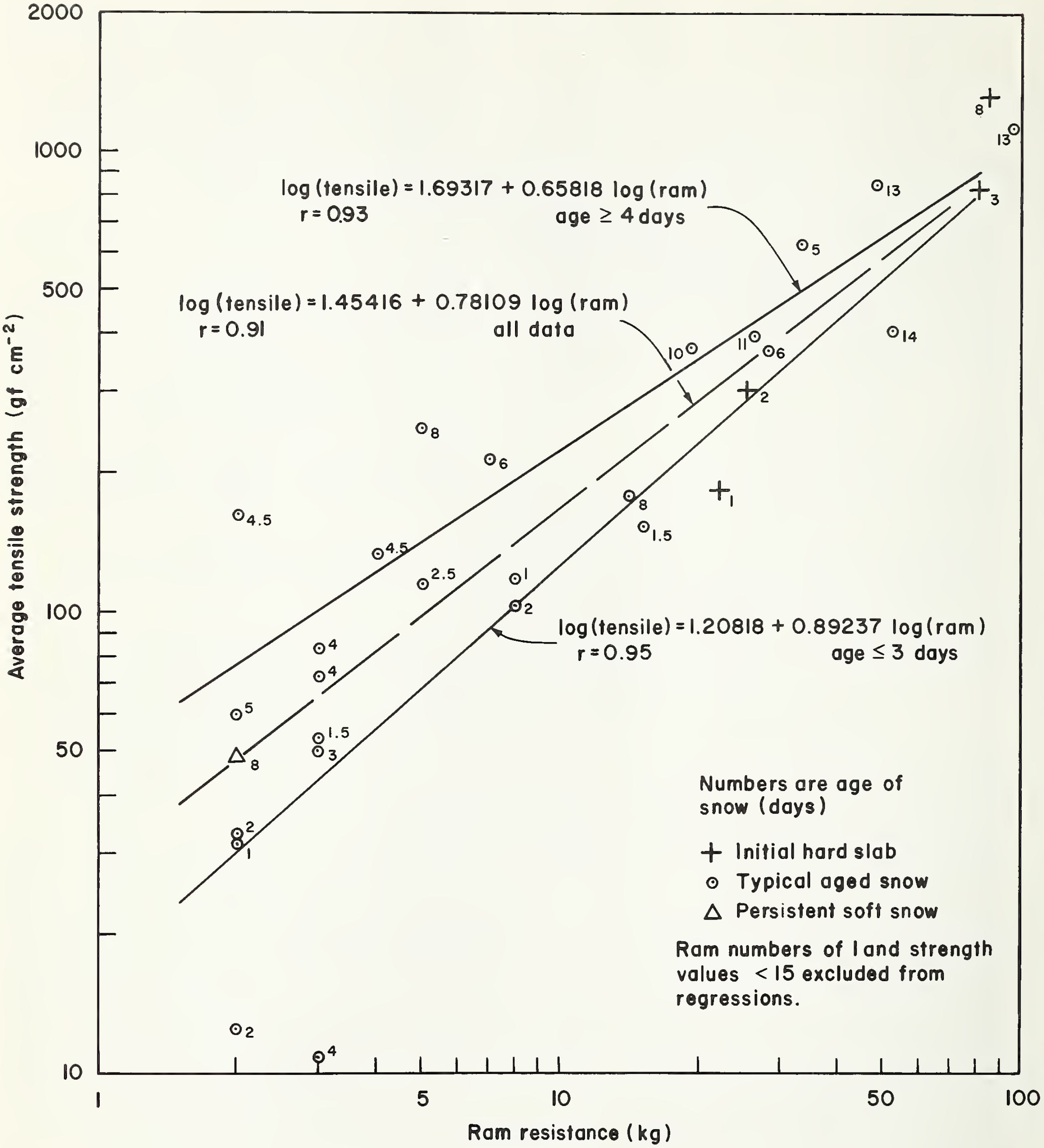


Figure 15.--Average tensile strength as a function of ram resistance and age.

Although our data do not justify further refinement of the ram resistance-time relationship, Hobbs (1965) found a linear log-log relation between ram resistance and time for artificially compacted snow, using data from Wuori (1963).

These discussions of ram resistance versus strength have been confined to tensile strength for the sake of brevity. Torque vane and shear frame strength follow the same general patterns, but with more scatter.

Any consideration of ram resistance is handicapped by the lack of sensitivity at low ram resistances. Ram resistances below 1 kg cannot be measured with existing instruments, and readings below 3 to 5 kg are not very accurate. A lightweight rammsonde with the same geometry as the original instrument but capable of readings as low as 0.1 kg is now being field tested by the U.S. Forest Service (Perla 1969). It should be very useful in soft, fresh snow.

Air Permeability

The coefficient of air permeability (K) reported here is defined by the equation

$$K = \frac{QL}{A\Delta P} = \frac{v}{i} \qquad (1)$$

where

- Q = volume of air (cm^3 sec^{-1})
- L = length of snow sample in the direction of airflow (cm)
- A = area of snow sample perpendicular to flow direction (cm^2)
- ΔP = pressure differential (cm of water)
- v = airflow velocity = Q/A (cm sec^{-1})
- i = pressure gradient = $\frac{\Delta P}{L}$ (cm of water per cm of length of sample)

The units of K are cm^2 sec^{-1} (cm of water)$^{-1}$. Some authors have erroneously canceled cm with (cm of water)$^{-1}$ and reported K in units of cm sec^{-1}. For comparative purposes, however, the numerical values of the K presented here can be compared directly to those reported as cm sec^{-1}. Our data were not corrected for the deviation of temperature from 0° C., nor were they adjusted back to sea level elevation.

The following test procedure was used to determine air permeability and change of permeability upon compaction of the snow:

1. A sample tube with the undisturbed snow still in it was placed in a holder that formed an airtight seal around the outside of the tube.
2. A vacuum pump created a pressure differential that pulled air through the sample.
3. Three flow rates and corresponding pressure drops were recorded for each sample.
4. Permeability was computed for these three sets of data.
5. The sample tube was removed from the holder, a rubber cap placed over one end, and the snow was compacted with a wooden ram.
6. The cap was removed from the tube, which was put back into the holder and subjected to a pressure differential.
7. Pressure drop and airflow through the compacted sample were recorded.
8. A new permeability was computed for the compacted sample.
9. Steps 5, 6, 7, and 8 were repeated for five compactions.
10. A graph of the ratio of permeability to porosity ($\frac{K}{n}$) as a function of permeability (K) was plotted for each sample.

One of the three airflow rates used in step 3 (usually the highest) was used in steps 6 and 9. Sample tubes were the standard SIPRE density samplers. Pressure differential was measured on a differential capacitance meter with a range of 0.001 to 30.0 mm of mercury. Airflow was measured by a floating sphere, three-flat-faces type flowmeter with a range of 0.009 to 0.03 cm sec^{-1} at 11,300 feet elevation.

Airflow velocities(v) were between 0.001 and 0.021 cm sec^{-1}, and pressure gradients (i) were mostly between 0.02 x 10^{-3} and 20.0 x 10^{-3} cm water/cm length of sample. These were kept several orders of magnitude lower than those commonly used (Bader 1954, Bender 1957, Ishida and Shimizu 1958, Ramseier 1963) to assure flow in the "laminar" range. Because of the lower velocities and pressure gradients, however, other problems, presumably associated with low flows through porous media, were encountered.

This technique was tedious, and the compaction in step 5 certainly changed the structure of the snow in a far different manner than the change produced by tapping or shaking a noncohesive granular material like sand or gravel. In spite of these difficulties, duplicate samples of a pair usually gave consistent results.

The coefficient of air permeability was found to vary with pressure differential and flow rate, although the velocities were well below the "turbulent" range:

Change in permeability as flow rate was increased	Percentage of total samples
Remained the same	42
Increased	30
Decreased	8
Decreased, then increased	10
Other	10

These changes in permeability with flow rate were determined on 61 samples of alpine snow ≤ 14 days old. Instrumentation error in determining permeability was approximately 15 percent.

There was no unique permeability; one of the three values computed in step 4 was selected to describe the sample. The permeability corresponding to the airflow rate used in steps 7 and 9, usually the highest applied to the undisturbed sample, is the one reported here.

For snow 2 weeks or less in age, the coefficient of air permeability (K) varied from 7.5 to 313 $cm^2\ sec^{-1}$ (cm of water)$^{-1}$. About 70 percent of the samples had permeabilities between 10 and 30 $cm^2\ sec^{-1}$ (cm of water)$^{-1}$. The relatively few samples older than 2 weeks or of unknown age had K's between 15 and 48 $cm^2\ sec^{-1}$ (cm of water)$^{-1}$. These values are about one order of magnitude lower than those often quoted for air velocities up to 5 to 10 cm sec^{-1}.

The low permeability values and the variation of permeability with flow rate may both result from the low flow rates used. Although much is written about avoiding high flow rates and the resulting "turbulent flow," little mention is made of the problems associated with low flow rates in granular materials except when pore spaces in the material approach the mean free path of air molecules (Scheidegger 1960).

Recently, Langfelder and coworkers (1968) reported soils studies where permeability increased with an increase in pressure gradient. They also showed a nonlinear relation between flow rates and pressure gradient for clay soils when flow rates were not much greater than ours. The threshold gradient for nonlinearity was different for different soils. If a similar shifting threshold gradient can be found for cold snow, the magnitude of the threshold may be more indicative of snow structure than such things as simple air permeability upon compaction. Such a discovery would also help explain the phenomena, since several of the possible explanations offered by Langfelder and coworkers (1968) were based upon the presence of free water in the sample, which would not be present in cold snow.

Figure 16, which follows the example of Ishida and Shimizu (1958), shows permeability is not a well-defined function of density and grain type. Even within a grain type, the variation in permeability with density is so large as to make the relationship valueless. The slightly metamorphosed, type b, snow had the greatest range of permeability. Low permeabilities with moderate to high densities were typical of the fine-grained old snow (type d), while coarser-grained old snow (e or d) had moderate to high (30-110 $cm^2\ sec^{-1}$ (cm of water)$^{-1}$) permeability with high density (300-500 kg m^{-3}). The bd mixture resembled type b snow more than type d in permeability and density.

The permeabilities found in this study fall into the lower edge or below the diagrams of permeability as a function of porosity given by Bader (1954, 1962) and Keeler (1968) (fig. 17). Our initial hard slab had not only lower permeability but also lower porosity (higher density) than the wind slab indicated by previous workers.

The most common analysis of air permeability for snow is based on the empirical expression of permeability (K) as a function of porosity (n) developed by Bader (1954, 1962) and later used by Bender (1957) and Ramseier (1963).

$$K = \frac{anN}{N-n} \text{ or } \frac{K}{n} = a + \frac{1}{N} K \qquad (2)$$

The constants N and a are determined graphically by plotting K/n against K for several porosities obtained by compacting each sample. $\frac{1}{N}$ is the slope and a is the K/n axis intercept for the linear part of the line.

N is called virtual porosity and is usually interpreted as the loosest possible packing for the texture. The ratio N/n is reported to be 1.063 (Bender 1957) to 1.058 (Bader 1954) for normal metamorphosed snow, and to approach 1.1 (Bader 1954) to 1.2 (Bender 1957) for wind-packed snow. With time, metamorphism is said to change the wind-packed ratio back to the "normal" ratio. The con-

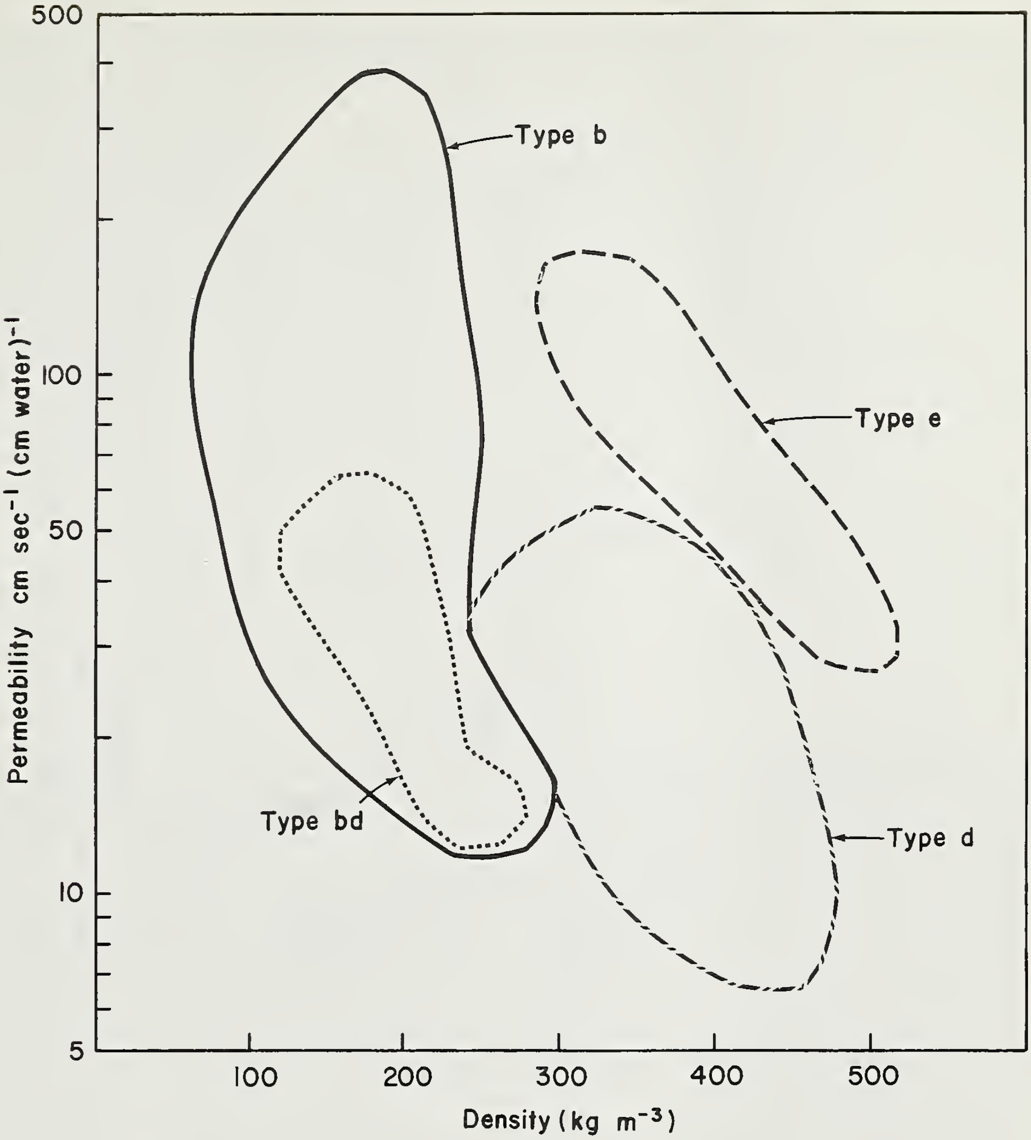


Figure 16.--Permeability to air as a function of density with grain types delineated.

stant "a" depends mostly on grain size. Bender (1957) suggests the relation is approximately

$$a = 16.8d^{1.63} \tag{3}$$

where d is grain diameter in mm.

The overall average of N/n for our data was 1.0554 for samples 14 days or younger and 1.0617 for all samples (tables 4 and 5). These agree well with the "normal" ratios of 1.063 and 1.058 reported earlier. The averages for initial hard slab, typical aged snow, and persistent soft snow were 1.08, 1.03, and 1.02, respectively (see table 6). These agree in principle, if not in absolute values, with the idea of larger ratios reflecting greater wind action.

Virtual porosity varied from 0.943 for very weak new snow to 0.444 for heavily metamorphosed old snow. Bender (1957) reports values from 0.92 to less than 0.50.

The above analyses were interesting for comparative purposes, but were of little diagnostic value. Several additional analyses were tried to see if more helpful relationships could be found.

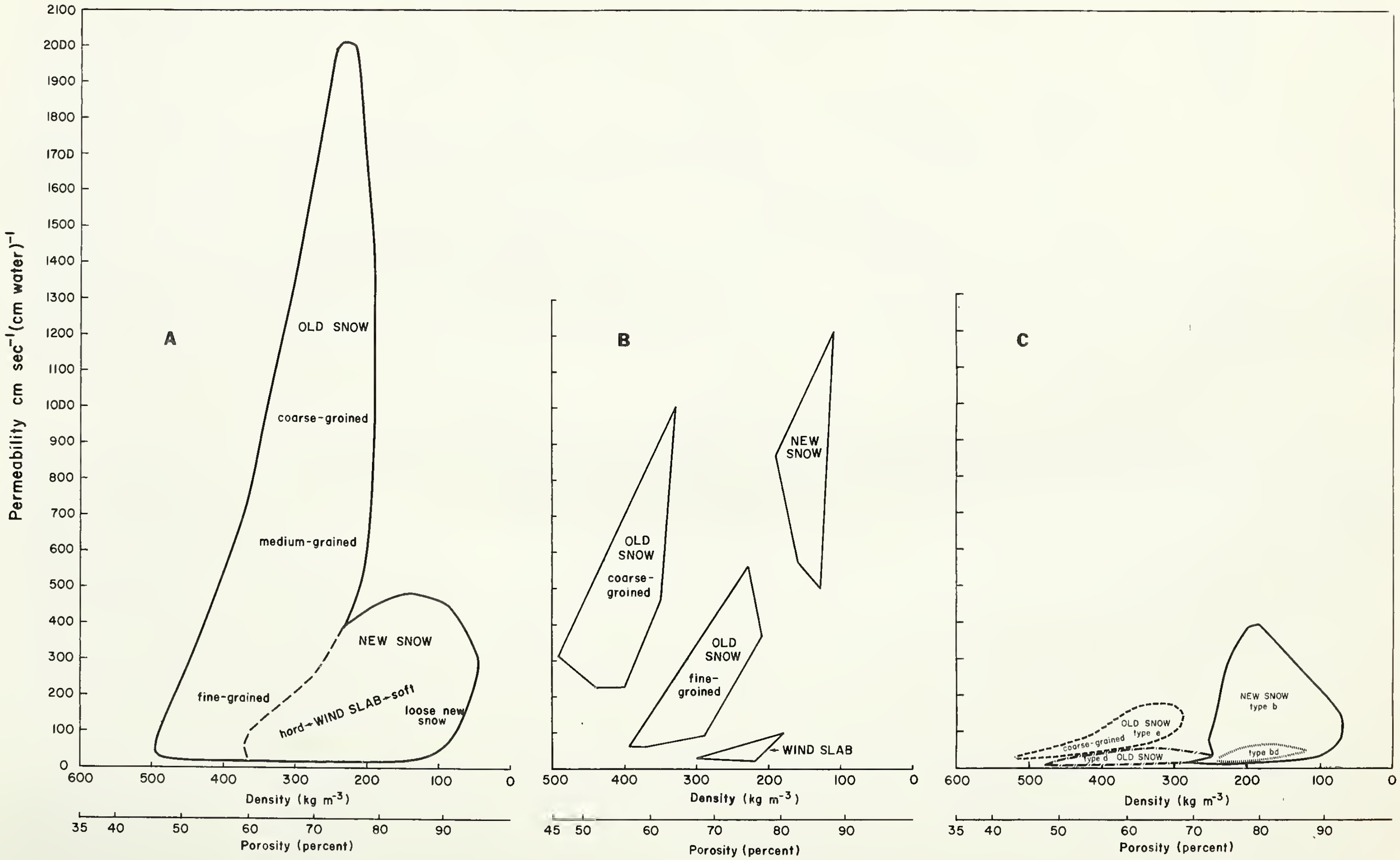


Figure 17.--Permeability to air as a function of porosity (density) after (A) Bader (1954), (B) Keeler (1968), and (C) this study.

Table 4.--Average N/n for snow 14 days old or younger, by sampling dates, where N = virtual porosity and n = actual porosity

Sampling date	N/n	Number of samples	Sampling date	N/n	Number of samples
20 Feb 68[1/]	1.0155	1	6 Jan 67	1.0551	4
13 Dec 66[2/]	1.0199	1	23 Feb 68	1.0558	8
3-4 Jan 67[1/]	1.0212	5	1 Feb 67	1.0600	6
15 Jan 67	1.0375	4	12 Feb 67	1.0646	10
2 Feb 68[1/]	1.0381	4	3-4 Feb 65	1.0742	6
28-29 Jan 65	1.0428	2	17 Jan 68	1.1657	2
29-30 Apr 68	1.0454	2			
31 Jan 67[1/]	1.0514	5	Average or total	1.0554	60

Additional samples less than 1.0:
1/ one.
2/ three.

Table 5.--Average N/n by age of snow for all data, where N = virtual porosity and n = actual porosity

Snow age (Days)	N/n			Number of samples
	Average	Maximum	Minimum	
0-3	1.0420	1.1176	1.0000	1/24
4-7	1.0556	1.0957	1.0066	2/21
8-14	1.0767	1.2245	1.0083	3/15
≥15 (or unknown)	1.0713	1.2438	1.0035	1/39
Overall average	1.0617			99

Additional samples less than 1.0:
1/ two.
2/ four.
3/ one.

In the first analysis, tensile strength was plotted against density with permeability classes indicated. This added nothing to the previous plot of tensile strength against density. However, a rearrangement of the same three variables to show permeability as a function of density with tensile strengths identified showed a very interesting pattern (fig. 18).

The use of permeability helped to clarify some of the scatter in the strength-density relation. For any given snow density there is apparently some intermediate permeability above and below which strength decreases. The axis of this "optimum permeability" sloped down and to the right, indicating lower optimum permeabilities for higher densities. To a large extent this axis also separated the older from the younger snow. Since permeability is usually considered an index of snow texture, figure 18 suggests that the strength of snow of a given density is greater for a certain textural arrangement than for any other. One explanation of the relationships shown in figure 18 hinges on the fact that snow of a given density can vary greatly in texture, which is generally defined as the spatial arrangement of grain centers and intergranular voids. A highly uniform texture with good grain-to-grain bonding and small, well-distributed flaws will have the maximum strength and intermediate permeability found along the axis of "optimum permeability." A change in texture toward larger grains, few and weaker bonds, and larger flaws will result in the weaker and more permeable snow found above the axis of "optimum permeability." On the other hand, a change from a highly uniform texture toward finer grains and a concentration of small, partially alined, but not necessarily communicating flaws will result in the

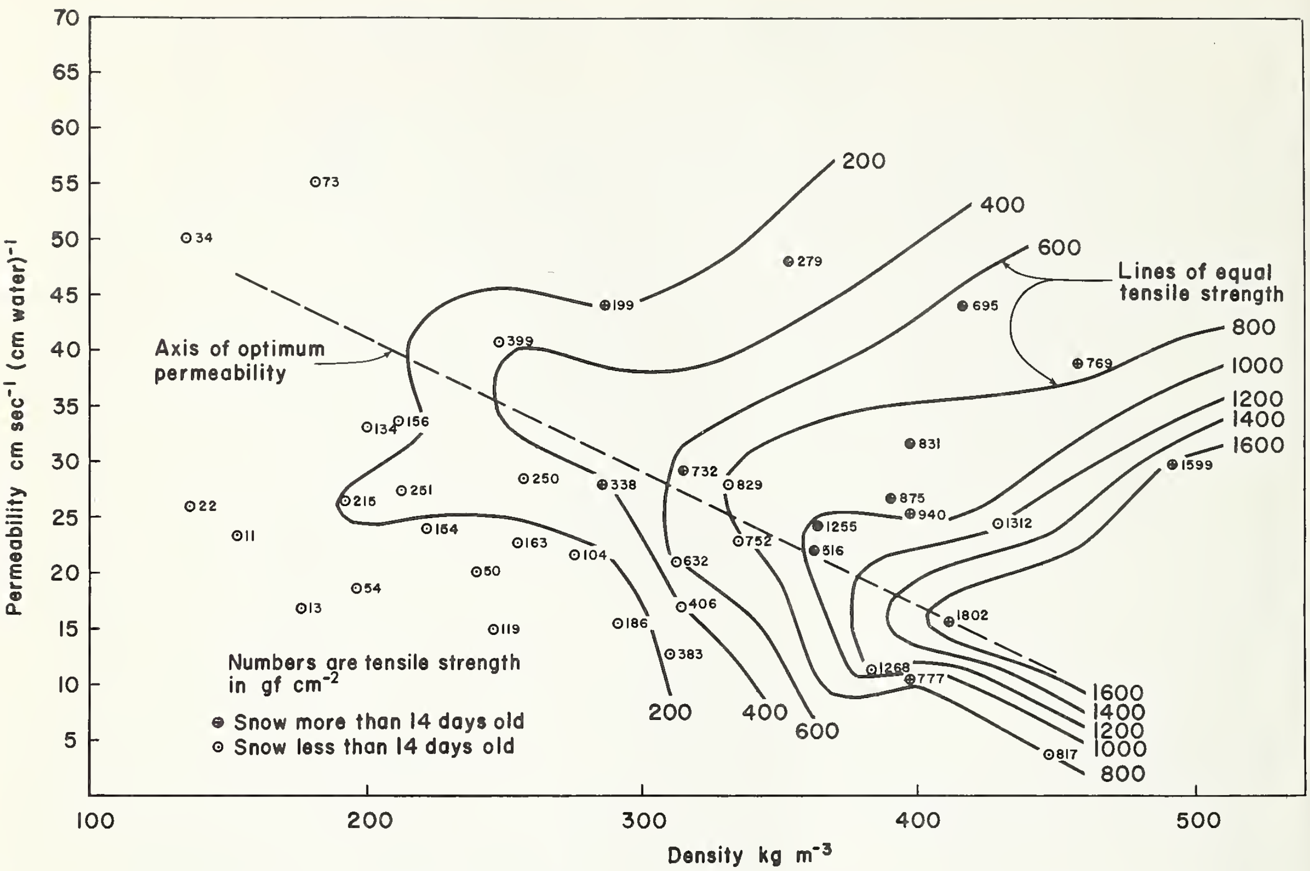


Figure 18.--Tensile strength as a function of density and air permeability; snow age not limited to 14 days or younger.

lower strength and relatively low permeability found below the axis of "optimum permeability." The slope of this axis toward lower permeability as density increases could be the result of a higher proportion of ice per unit area for a given texture rather than a change in texture. In spite of the formidable difficulties in making detailed measurements of the size, shape, and arrangement of grains and intergranular spaces, there is no other immediate prospect for a direct check of how these features actually relate to permeability and strength.

Snow Cover Properties as Related to Weather Conditions

Weather conditions during and following deposition of 17 snow layers are summarized (table 6) in an attempt to isolate the conditions that caused unusual density, strength, and hardness of the snow. Fifteen layers 3 days or less in age and two about twice that age were selected for study. Based on the density-age relationship discussed earlier in this paper, 3 of the layers were initial hard slab, 11 were typical aged snow, and 3 were persistent soft snow.

Hard slab has generally been considered the product of strong winds and low temperatures. Our limited sample tends to confirm this idea.

When initial hard slab was being deposited during our studies, winds averaged 1.5 times those when more typical deposition was taking place, and 2 times those during the deposition of persistent soft snow. Thus, high winds appear correlated to hard slab formation.

Average air temperatures during deposition decreased from periods of persistent soft snow, to typical aged snow, to initial hard slab. There was

Table 6.--Summary of weather and snow conditions for 17 snow layers in the alpine zone of Colorado

Date	Time of deposition	WEATHER CONDITIONS: During deposition: Wind: Average speed	Duration	Prevailing direction	Maximum--1hr.	Maximum--6hr.	Average air temperature	Precipitation	Accumulated snow	Drift Ratio	After deposition: Wind: Average speed	Duration	Prevailing direction	Average air temperature	Subsequent precipitation until pit was dug	SNOW CONDITIONS: Date snow pit was dug	Age	Density	Temperature	Ram No.	Tensile strength	Permeability	N/n
		mph	hrs		mph	mph	°F	cm	cm		mph	hrs		°F	cm		Days	kg m^{-3}	°C	kg	gf cm^{-2}	$\frac{cm^2}{sec\ (cm\ water)}$	
TYPICAL AGED SNOW--3 DAYS OLD OR YOUNGER																							
3-4 Jan 67	1700-0600	18.5	14	NW	24	21	10	0.051	0.716	14	9.6	5	Var	12	0.000	4 Jan 67	0.5	35.8	- 7.8	--	1	--	--
6 Dec 66	0800-1100	7.8	4	--	13	--	26	.305	.718	2	--	--	--	25	1.346	7 Dec 66	1.0	119.6	- 6.2	1	6	--	--
19 Feb 68[1]	0000-2400	17.2	24	NW	21	20	18	1.420	7.370	5	11.8	9	NW	20	.051	20 Feb 68	1.0	245.5	- 7.2	8	119	15	1.02
31 Jan-1 Feb 68	1000-0900	7.6	23	WNW	24	16	8	.686	3.090	4	9.6	25	NNW	5	.051	2 Feb 68	1.5	220.7	-16.0	15	154	24	1.03
10 Feb 67[1]	0000-2400	13.1	24	WNW	17	15	4	.330	1.961	6	9.3	12	WSW	9	.152	12 Feb 68	1.5	196.1	-11.7	3	54	19	1.06
1 Jan 67[1]	0000-2400	12.8	24	NNW	22	19	4	.406	3.510	9	11.8	36	NNW	-4	.254	3 Jan 67	2.0	175.5	-16.3	2	12	17	1.04
2-3 Jan 67	1200-1200	12.2	24	NNW	25	14	-6	.559	5.392	10	13.0	70	NW	10	.483	6 Jan 67	2.0	134.8	- 9.0	2	34	50	1.02
5-6 Dec 66	1300-0700	8.8	19	SE	14	10	19	2.770	1.680	1	--	--	--	25	1.651	7 Dec 66	2.0	104.8	- 5.5	1	22	--	--
10 Feb 67[1]	0000-2400	16.0	24	WNW	30	24	8	.889	7.780	9	11.8	36	NNW	5	.483	12 Feb 67	2.0	274.2	-11.8	8	104	22	1.02
2 Mar 66[2]	0000-2400	10.6	24	SW	18	15	8	.127	4.240	33	16.6	60	NNW	-7	.152	5 Mar 66	2.5	235.4	-16.8	5	116	--	--
1 Jan 67[1]	0000-2400	12.8	24	NNW	22	19	4	.406	3.510	9	17.9	59	NNW	2	.305	4 Jan 67	3.0	136.0	--	--	26	26	1.00
Average		12.5	21		21	17	9	.723	3.633	9	12.4			9	.448		1.7	170.8	-10.8	5	59	25	[3]1.03
INITIAL HARD SLAB--3 DAYS OLD OR YOUNGER																							
1 Feb 68	0900-1400	21.8	5	WNW	30	--	6	0.000	4.650	∞	6.5	19	NNW	6	0.025	2 Feb 68	1.0	290.6	-18.1	22	186	15	1.04
3 Mar 65[2]	0000-2400	18.3	24	NNW	24	22	-7	.152	9.240	61	15.4	36	NNW	-7	.000	5 Mar 66	2.0	355.4	-20.9	25	307	--	--
9 Feb 67[1]	0000-2400	18.6	24	WNW	34	29	13	.152	12.591	83	13.5	60	NW	6	1.372	12 Feb 67	3.0	446.6	-12.4	80	817	7	1.12
Average		19.6	18		29	26	4	.101	8.831	72	11.8			2	.466		2.0	364.2	-17.1	42	437	11	[3]1.08
PERSISTENT SOFT SNOW																							
22 Feb 68	0000-0900	12.3	9	NNW	14	13	16	2.110	2.460	1	11.8	25	NW	14	1.219	23 Feb 68	1.5	70.3	- 7.8	2	5	103	1.02
6 Dec 66[4]	0000-2400	6.1	14	SE	13	8	23	2.400	3.600	2	5.8	156	N	7	1.295	13 Dec 66	7.0	162.2	- 8.8	2	4	137	([3])
5 Dec 66[4]	0000-2400	9.2	24	S	14	12	22	2.900	4.200	1	7.4	134	N	9	3.581	13 Feb 66	8.0	167.7	- 5.4	2	49	314	1.02
Average		9.2	16		14	11	20	2.470	3.420	1	8.3			10	2.497		5.5	133.4	- 7.3	2	19	185	[3]1.02

1/ Stake readings too far apart for good drift ratios.
2/ Dating of hard and soft slab is arbitrary--based on winds and temperature.
3/ Value less than 1.0 omitted from averages.
4/ Deposition periods were arbitrarily set at 24 hours for lack of more specific data.

also a tendency for air temperatures following the deposition of initial hard slab to be lower than for the other two types of snow. In spite of the averages, there were a few examples of subzero Fahrenheit temperatures during and following the deposition of typical aged snow. In general, however, the case for low temperatures during hard slab formation is reasonably well substantiated by our data.

Another parameter that seems to distinguish periods of initial hard slab deposition is the drift ratio. In our case, this is the water equivalent of the snow layer in the avalanche paths divided by the water equivalent of the precipitation (in Q-12 Park) that fell during the deposition period. Low ratios indicate little wind deposition; high ones indicate heavy wind deposition. The drift ratio during periods of hard slab deposition averaged 8 times that during the deposition of typical snow, and 50 times that during deposition of persistent soft snow. Much of the scatter in the drift ratios is probably due to inaccurate dating of the deposition. When snow stakes were read only once or twice per week, the age of many layers had to be determined somewhat arbitrarily. An accurate evaluation of the drift ratio will have to await more detailed field data.

From our limited sample, initial hard slab appears to require high winds, low temperatures, and a high drift ratio. The two layers of typical aged snow at 1 day and 245.5 kg m^{-3} and at 2 days and 274.2 kg m^{-3} (fig. 2; table 6) illustrate this point. In both cases winds were only slightly below the average for initial hard slab, but the drift ratios were very low and in one case air temperature was quite high. As a result, densities were just on the border between typical aged snow and initial hard slab.

The two samples of older snow measured on December 13, 1966 were 7 and 8 days old, yet they had the density, hardness, and strength of snow less than half that age (see Appendix). This snow was deposited by a large storm that produced 1.24 inches of water in the 24 hours, and 1.74 inches in the 48 hours following noon on December 5. Winds were light during and following the storm; two-thirds of the hourly winds in the post-deposition period were below 10 m.p.h. and none above 18 m.p.h. Temperatures averaged 22° F. during the storm, dropped below 0° F. afterward, remained 0° to 10° F. for 1.5 days, then increased with daytime temperature reaching the mid-20's for the remainder of the period.

The light winds during and after the storm allowed the snow to fall with little or no breakage. After the storm, cold temperatures slowed metamorphism and the light winds were not enough to cause the snow to drift. The slight warming trend toward the end of the period apparently did not reduce the cold content of the pack enough to permit rapid metamorphism before the samples were taken.

Our best example of the influence of weather conditions on snow properties was recorded in early February 1968. During the 23 hours preceding 0900 hours on February 1, winds averaged 7.6 m.p.h. with 24 m.p.h. for the windiest hour and 15.5 m.p.h. for the maximum 6-hour period. The 14 cm of deposition had 4.5 times the water equivalent of the precipitation. It was called typical aged snow on the basis of the age-density relation, although its density approached the upper limit and its ram number and tensile strength were three times the average for this type snow. At about 0900 hours on February 1, the wind increased and precipitation stopped. For the next 5 hours, winds averaged 21.8 m.p.h. with a maximum hour of 30 m.p.h. The 16 cm of deposition was all drift snow. In spite of being 6 to 8 hours younger, this snow was appreciably denser, harder, and stronger than the layer just below (see Appendix). Wind and the accompanying drift snow seem to be the major factors contributing to this change in physical properties, although temperatures did drop slightly.

The 4-cm layer of soft snow at 462-cm height in the pit of February 12, 1967 (see Appendix) is another example of a change in snow stratigraphy reflecting weather conditions during deposition. Although we cannot be sure of the dating, it seems likely this layer was deposited between 1800 hours on February 6 and 1200 hours on February 7. During this time, 0.25 inch (0.635 cm) of water was added to the pack by precipitation; air temperature averaged about 3° F., the winds averaged 11 m.p.h., and the drift ratio was 1.7. The 30-cm layer of tough snow just above the thin, soft layer was probably deposited on February 9, 1967. During this 24-hour period, there was 0.06 inch (0.1524 cm) of precipitation; temperatures averaged 13° F. and winds 18.6 m.p.h. The drift ratio was 82.6. This dense, hard layer was almost completely drift snow put in by high winds (maximum

6-hour period averaged 29 m.p.h.). Temperatures were moderate (13° F.) during deposition and a little colder (6.4° F.) during the 60-hour post-deposition period. The switch from moderate precipitation with little or no wind to very light precipitation and strong winds seems the most likely reason for this dramatic change in snow properties. Temperatures did not follow the expected pattern.

The 4-cm layer of soft, weak snow, sandwiched between two hard, tough layers was obvious when the pit wall was examined. It also showed up in the tensile strength, density, and ram resistance data. Because such weak layers frequently form the basal shear plane of avalanches, it is important to locate them in the pack. When weak layers are only a centimeter or less in thickness, however, it is very difficult to detect them with conventional field techniques. Noel C. Gardner (personal communication), working in British Columbia, Canada, found that weak layers appeared brighter than others when a strong light was put behind a vertical section of snow at night.

Some field men have long suspected that extremely high winds (50-70 m.p.h.) do not form hard slab; others say such winds produce "very hard" slab but few slab avalanches. Our data give no information on a possible upper wind threshold for hard-slab formation.

Summary and Conclusions

The average age of the snow studied was 5 days, and most of it did not exceed 14 days. Density varied from 40 to 450 kg m^{-3} with the latter value measured in 3-day-old snow 50-60 cm below the surface. Samples taken parallel and perpendicular to the layering within a layer showed no significant density differences. Three types of snow were distinguished on the basis of the density-age relation: high-density young snow—called initial hard slab; low-density old snow—called persistent soft snow; the remainder—called typical aged snow. The last two types would be called soft slab by the field man. There is little doubt these three types form a continuous array rather than three discrete populations.

Most of the avalanches that ran on days when initial hard slab was observed in the study pits were of the hard slab variety. Soft-slab avalanches predominated on days when typical aged or persistent soft snow were found in the pits. For the entire 3 years of study, initial hard slab appeared in 15 percent of the pits. During the 18-year period 1950-68, however, hard-slab avalanches accounted for about 30 percent of the total avalanches on nearby paths. Apparently many of the hard-slab avalanches in this part of Colorado involved old snow.

Tensile strength as measured by the centrifugal or spin tester varied over three orders of magnitude. Although strength generally increased with density, there was a tendency for the younger snows to be weaker than older snows of the same density.

Shear strength was measured by the torque vane and also by a small open shear frame. The relation between tensile strength and shear strength as measured by the torque vane was about 1:1. Shear strength as measured by the frame was lower than any of the other strength indexes.

The relation between tensile strength and shear strength as measured with the shear frame varied with strength and age. The ratio of tensile to shear frame strength was about six to one for strong snow layers, but decreased to less than two to one for weak snow. When age was considered, the six-to-one ratio was characteristic of snow 10 to 14 days old, while the lower ratio applied to young snow.

The logarithm of ram resistance showed a positive linear correlation with density that was not greatly different from the correlations found for polar snow and for seasonal snow cover of several other Western States. Snow from wind-exposed alpine areas had a higher ram resistance for a given density than snow from a nearby opening in the trees.

The coefficient of air permeability was between 10 and 30 cm^2 sec^{-1} (cm of water)$^{-1}$ for 70 percent of the samples. This is about one order of magnitude lower than expected. Permeability was found to vary with flow rate and pressure differential when flow rates were low. The ratio of virtual porosity to actual porosity averaged 1.062 for snow no more than 14 days old. This confirms previous data for "average metamorphosed" snow. The averages for initial hard slab, typical aged snow, and persistent soft snow were 1.08, 1.03, and 1.02, respectively. Although on the average this ratio distinguishes initial hard slab, the difficulty in making the measurement and the scatter of individual readings make it useless as a field guide.

Air permeability helps explain some of the scatter in the strength-density relation. For snow of a given density, there appears to be some intermediate or "optimum" permeability above and below which strength decreases. Furthermore, this optimum permeability decreases with an increase in density. To the extent permeability is an index of texture, this means strength is a function of density and texture.

Initial hard slab was correlated with moderate to high windspeed, cold temperatures, and the presence of wind-transported snow.

No good way was discovered to distinguish between hard slab that was formed in just a few days (initial hard slab) and that which formed over a longer period of time. Even though we have shown that younger snow has lower strength for a given density than older snow, this is not well enough documented to be diagnostic.

The relatively numerous hard-slab avalanches reported from the high alpine area west of Denver, Colorado, are probably due to several things. Undoubtedly the initial hard slab described in this report is one factor. Another important factor, however, is that in this region of relatively low snowfall both natural and artificial triggers often release hard older layers.

This study indicated the need for fast and simple **in situ** methods for measuring the mechanical and physical properties of low-density fresh snow. One thing that would be especially useful would be a lightweight rammsonde, and another would be a better classification scheme for snow on the ground.

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APPENDIX

Summary of Physical and Mechanical Properties of Alpine Snow--Mostly Less Than 2 Weeks of Age

Date	Location	Grain size and type[1]	Tem-pera-ture	Density	Ram no.	Age	STRENGTH INDICES Torque vane	Shear frame	Tensile (spin)	Average tensile	Average density	Height above datum	Density	Poros-ity n	Vir-tual poros-ity N	N/n	"a"[2]	Per-mea-bility	Aver-age per-mea-bility	Remarks
		mm	°C	kg m^{-3}	kg	days	--	gf cm^{-2}	--	--	kg m^{-3}	cm	kg m^{-3}					cm^2/sec (cm water)		
1965																				
28-29 Jan.	LIFT GULLY											171 Snow surface								
		a	-12.0			< 1		6.1				157								
		a	-13.0			< 1						145	121.4	0.868						
		0.5 b	-14.0			2						118	239.0	.739	0.758	1.0252	3.5	66.56*		*Permeabilities for this run may be poor because samples stayed in tubes overnight.
		<.5 b	-14.0			3		29.4				83								
												75	228.8	.750	.795	1.0605	3.0	42.19		
		1.0 d	-10.4	197.6		--		45.4				28	197.6	.784	.867	1.1055	17.2	156.00		
												-5*	315.6	.655	.714	1.0905	8.0	117.91		*Below basal failure plane of avalanche.
3-4 Feb.	LIFT GULLY											230 Snow surface								
		1.0 d	-6.2	340.6	9	≲ 6		60.5				220	340.6	.628	.682	1.0860	2.4	21.20		Tests taken just above fracture line of hard-slab avalanche
		<.5 d	-9.9	330.2	15	≲ 6						200	330.2	.630	.659	1.0460	2.4	25.85		
		.5 d	-11.5	316.8	40	≲ 6	99.2	70.8				180	316.8	.654	.692	1.0581	2.0	24.45		
		<.5 d	-11.3	336.0	35	≲ 6						160	336.0	.634	.679	1.0710	1.8	20.00		
		<.5 d	-11.0	316.2	44	6	252.0	82.4				140	316.2	.655	.709	1.0886	1.5	16.19		
		<.5 d	-8.5	--	9	6	102.0	114.0				115								
		<.5 d	-8.2	322.4	9	6						110	322.4	.649	.711	1.0955	0.5	3.98		
		<.5 d	-6.0	308.6	35	--						85	308.6	.663	.704	1.0618	1.4	17.91		
						--	266.0	125.5				80								Basal failure plane of avalanche was at 60 cm height.
		3.0 e	-2.8	--	6	--	28.3	86.5				55								
		3.0 e	-2.7	332.4	6	--						50	332.4	.638				65.95		
		3.0 e	-2.1	290.2	6	--						20	290.2	.684				114.90		
15-16 Mar.	URAD #5											343 Snow surface								Tests taken in snow uphill from fracture line of a soft slab avalanche that ran 24 hours previously.
		.5 b	-9.7		1	<14						313	229.8	.749	.792	1.0574	3.0	49.06	58.44	
													216.6	.763	.792	1.0380	3.0	67.82		
		.5 b	-9.7		2	<14	28.3	7.6				290	241.8	.736	.808	1.0978	2.5	40.83	55.88	
													161.6	.823	.857	1.0413	2.5	70.94		
		.5 b	-9.2		2	<14						262	222.2	.758	.772	1.0185	2.0	60.68	50.05	
													241.2	.737	.772	1.0475	2.0	39.42		
		.5 b	-8.8		10	<14	34.0	21.5				255								
		---	--		3		146.0					210	338.6	.630	.692	1.0984	15.0	102.48	102.77	Basal failure plane of avalanche was at 230 cm.
													337.0	.632	.692	1.0949	15.0	103.06		

[1] Snow types are those given in International Association of Hydrology. Commission on Snow and Ice, 1954.
[2] See equationa 2 and 3, p. 20 and 21.

Summary of Physical and Mechanical Properties of Alpine Snow--Mostly Less Than 2 Weeks of Age--continued

Date	Location	Grain size and type[1]	Temperature	Density	Ram no.	Age	STRENGTH INDICES Torque vane	Shear frame	Tensile (spin)	Average tensile	Average density	Height above datum	Density	Porosity n	Virtual porosity N	N/n	"a"^{2}	Permeability	Average permeability	Remarks
		mm	°C	kg m^{-3}	kg	days	- -	gf cm^{-2}	- -	- -	kg m^{-3}	cm	kg m^{-3}					cm^2/sec (cm water)		
5 Mar. '66	BELAY POST 4											50	Snow surface							
		--	-20.9		25	2	183.2			306.7	355.4	30								Initial hard slab (Average of 5 samples)
		--	-16.8		5	2½	34.0			116.2	235.4	12								Top layer of snow was harder and tougher than older layer below. (Average of 3 samples.)
1966-1967																				
7 Dec. '66	BELAY POST 4											161	Snow surface							Fresh snow very soft slab
		b	-6.2	118.2	1	1	5.7	3.8	4.2	6.1	119.6	145								
				121.0					8.0											
		0.5 b	-5.5	106.6	1	2		6.4	22.4	21.5	104.9	125								
				103.2					20.6											
13 Dec. '66	BELAY POST 5											102	Snow surface							Snow soft - Density tubes dropped out of sight.
		2.0 a	-8.4		1							100								
		.4 b	-8.8		2	7						84	170.2	.815	.675	.8280	3.0	--	136.82	
													169.4	.816	.727	.8909	3.0	136.82		
		.4 b	-8.8	162.2	2	7	6.7	5.8	4.2	4.2	162.2	81								Persistent soft snow
				164.0																
		.4 b	-7.2		2	7						76	174.6	.809	.800	.9888	5.0	384.05	313.86	
													180.4	.804	.820	1.0199	8.0	243.67		
		.4 d	-5.4	172.6	2	8	8.0	9.4	46.4	49.2	167.7	65								Persistent soft snow
				162.8					51.9											
		2.0 de	--	301.2	3	--						8								
3 Jan. '67	BELAY POST 4											175	Snow surface							
		.7 bd	-16.3	176.4	2	2	11.4	8.4	18.2	12.5	175.5	163	214.4	.767	.813	1.0500	1.8	20.08	16.92	
				174.6					6.9				221.6	.758	.787	1.0380	1.6	13.76		
4 Jan. '67	BELAY POST 4											230	Snow surface							Same snow as that tested 3 Jan 67.
	Pit 2	--	--	173.2					32.0			200								
		--	--	147.0	--	3	39.0	13.6	28.4	21.5	136.0									
		--	--	138.0					14.5											
		--	--	85.6					11.2			190	204.6	.777	.775	.9970	1.0	14.52	26.00	
													186.4	.797	.800	1.0040	1.2	37.48		
	Pit 1											42	Snow surface							Snow at 32 cm height less than 18 hours old.
		1.5 a	-7.8	36.2	--	½			1.0	1.2	35.8	32								
				35.4					1.4											
		.5 b	-12.5			3						5	154.0	.832	.831	1.0000	1.7	22.89	25.28	
													116.4	.873	.885	1.0140	1.7	27.68		
6 Jan. '67	N. CHUTE OF CLIFFS											97	Snow surface							
		bd	-9.0	122.2	2	2	18.5	15.1	27.9	33.6	134.8	66	133.2	.855	.873	1.0211	2.4	50.01	50.40	
				147.4					39.3				135.6	.852	.879	1.0317	2.0	50.80		
		bd	-7.7	156.2	3	4	24.2	--	9.5	10.9	153.0	45	214.6	.766	.821	1.0718	2.2	20.56	23.46	
				149.8					12.2				198.0	.784	.859	1.0957	2.5	26.37		

Summary of Physical and Mechanical Properties of Alpine Snow--Mostly Less Than 2 Weeks of Age--continued

Date	Location	Grain size and type[1]	Temperature	Density	Ram no.	Age	STRENGTH INDICES Torque vane	Shear frame	Tensile (spin)	Average tensile	Average density	Height above datum	Density	Porosity n	Virtual porosity N	N/n	"a"^{2}	Permeability	Average permeability	Remarks
		mm	°C	kg m^{-3}	kg	days	- -	gf cm^{-2}	- -	- -	kg m^{-3}	cm	kg m^{-3}					$\frac{cm^2}{sec\ (cm\ water)}$		
15 Jan. '67	BELAY POST 4											202	Snow surface							
		.6 b	-8.5	101.6 102.4	2	2					102.0	200								
		.6 b	-9.8			8	77.0					192	249.8 262.6	.727 .713	.733 .736	1.0083 1.0323	2.9 3.7	20.04 18.36	19.20	Probably extends into d layer too.
		.3 d	-10.2	321.8 346.0	14	8	262.0	105.5	179.8* --	179.8*	321.8	186								*Sample may have been cracked.
		.2 d	-10.4	303.0 312.8	19	10	150.9	83.0	358.9 406.3	382.6	307.9	168	320.8 309.6	.650 .662	.679 .705	1.0446 1.0650	1.5 2.2	12.79 12.70	12.74	
31 Jan. '67	BELAY POST 4											301	Snow surface							
		.7 bd	-9.0	255.2 239.8 244.2	2	4½	51.3	38.2	161.6 -- --	161.6	255.2	277	213.8 226.0	.767 .754	.777 .800	1.0130 1.0610	0.6 3.1	17.30 27.85	22.58	
		.7 bd	-10.4		5	8						250	200.2 194.6	.782 .787	.800 .824	1.0230 1.0470	2.2 2.7	25.40 29.45	27.42	
		.7 bd	-10.4	215.4 194.2 208.2	5	8	53.2	54.5	255.1 -- 246.6	250.8	211.8	246								
		.5 d	-10.2	335.8 326.4 330.4	48	13	697.5	120.0	944.9 859.6 682.9	829.1	330.9	218	342.2 320.4	.627 .651	.698 .650	1.1132 .9985	8.6 1.7	29.82 25.88	27.85	
1 Feb. '67	BELAY POST 3											465	Snow surface							
		.7 bd	-10.4	207.2 201.2 200.8	4	4½	59.8	27.6	--- 124.3 143.0	133.6	201.0	435	210.8 214.8	.770 .766	.824 .794	1.0701 1.0366	3.0 3.3	36.55 29.45	33.00	
		.7 bd	-12.6	172.0 201.8 201.2	7	6	115.4	45.4	185.0 263.4 196.8	215.1	191.7	395	224.6 232.0	.755 .747	.760 .778	1.0066 1.0415	1.6 2.4	28.99 24.04	26.52	
		.4 d	-13.0	382.8 382.8 383.4	98	13	1835.5	--	858.8* 1396.3 1547.9	1267.7	383.0	330	390.2 389.0	.575 .576	.639 .630	1.1113 1.0938	0.9 1.1	10.01 12.62	11.32	*This reading may be bad.

Summary of Physical and Mechanical Properties of Alpine Snow--Mostly Less Than 2 Weeks of Age--continued

Date	Location	Grain size and type[1]	Tem-pera-ture	Density	Ram no.	Age	STRENGTH INDICES Torque vane	Shear frame	Tensile (spin)	Average tensile	Average density	Height above datum	Density	Poros-ity n	Vir-tual poros-ity N	N/n	"a"^{2}	Per-mea-bility	Aver-age per-mea-bility	Remarks
		mm	°C	kg m^{-3}	kg	days	- -	gf cm^{-2}	- -	- -	kg m^{-3}	cm	kg m^{-3}					$\frac{cm^2}{sec\ (cm\ water)}$		
12 Feb. '67	BELAY POST 3											553 Snow surface								
		.5 b	-11.7	192.2 200.0	3	1½	42.8	17.7	51.3 57.4	54.4	196.1	541	215.0 222.6	.766 .757	.806 .800	1.0522 1.0568	1.3 1.6	19.77 17.40	18.58	
		.5 b	-11.8	286.4 263.4	8	2	111.0	30.4	151.8 55.4	103.6	274.9	521	235.2 246.8	.744 .731	.769 .748	1.0336 1.0233	1.8 1.6	24.27 18.90	21.58	Not quite initial hard slab.
		.5 d	-12.6		95	2½						498	449.8 448.6	.509 .510	.568 .510	1.1159 1.1176	1.4 1.4	7.38 7.11	7.24	
		.5 d	-12.4	445.6 447.6	80	3	1112.0	186.6	999.6 634.9	817.0	446.6	488								Initial hard slab.
		.5 d	-12.8		65	5						478	396.2 384.2	.568 .581	.597 .611	1.0511 1.0516	1.1 1.1	11.36 10.71	11.03	
		.8 d	-13.0	277.4 274.2 266.0	28	6	--	49.2	-- 388.9 358.8	373.8	270.1	465								Narrow soft layer.
		.5 d	-13.2	434.8 424.0	85	8	-- -	169.2	909.7 1711.8	1311.7	429.4	431	413.2 434.8	.550 .526	.559 .593	1.0164 1.1274	1.4 1.7	37.94 11.00	24.47	Initial hard slab.
1967-1968																				
7-8 Dec. '67	BELAY POST 4											218 Snow surface								Above fracture line of hard-slab avalanche.
		.7 bd	-13.4	206.4 240.8 239.4 222.0	3	3	24.7	4.5*	-- -- 50.3 5.7*	50.3	239.4	209	210.0 217.4 213.8 215.0	.771 .763 .767 .766	-- -- -- .796	-- -- -- 1.0392	-- -- -- 1.2	-- -- 21.32 18.35	19.84	*Bad readings.
		.4 d	-11.7	411.6 396.8 397.6	120	--	716.7	--	-- 890.2 664.8	777.5	397.2	176	407.2 409.0	.556 .554	.609 .608	1.0953 1.0975	1.6 2.8	10.95 10.05	10.50	
		.4 d	-6.3	364.4 362.4	44	--	755.1	116.3	561.9 470.7	516.3	363.4	95	353.2 361.2	.615 .606	.634 .628	1.0309 1.0363	2.5 2.2	24.81 19.67	22.24	
		1.2 d --	-3.8	290.0 282.2	15	--	--	--	226.5 172.4	199.4	286.1	50	309.0 322.6	.663 .648	.732 .806	1.1041 1.2438	7.6 12.2	42.08 46.68	44.38	Basal shear plane of avalanche at 42 cm.
		--	-2.3	353.0	18	--	58.9	34.8	279.3	279.3	353.0	20	335.6	.634	.667	1.0520	10.0	48.43	48.43	
21 Dec. '67	LIFT GULLY											184 Snow surface								Sonic boom test--above fracture line of soft slab-avalanche.
		--	-22.7	204.0 209.2 209.0	5	≤1	--	--	-- -- --	--	207.4	165								
		--	-22.4	182.2 176.0 175.0	2	≤1	--	--	12.9 5.1* 52.0	32.4	177.7	154								*Bad reading - not used in average.
		--	-21.9	--				8.7				145								Basal shear plane of avalanche @ 145 cm.

Summary of Physical and Mechanical Properties of Alpine Snow--Mostly Less Than 2 Weeks of Age--continued

Date	Location	Grain size and type[1]	Tem-pera-ture	Density	Ram no.	Age	STRENGTH INDICES Torque vane	Shear frame	Tensile (spin)	Average tensile	Average density	Height above datum	Density	Poros-ity n	Vir-tual poros-ity N	N/n	"a"²	Per mea bility	Aver-age per-mea-bility	Remarks
		mm	°C	kg m⁻³	kg	days	- -	gf cm⁻²	- -	- -	kg m⁻³	cm	kg m⁻³					cm² / sec (cm water)		
17-19 Jan. '68	STATION 3											436	Snow surface							
		.5 b	-10.9	183.2 183.6	2	5	31.3	14.8	22.8 97.3	60.0	183.4	431								Deep pit - midwinter.
		.5 d	-13.7	313.6 314.0	52	14	262.2	53.4	407.3 407.8	407.6	313.8	405	334.2 333.0	.636 .637	.704 .780	1.1069 1.2245	1.8 1.8	16.77 17.30	17.04	
		.5 d	-13.2	284.0 285.2	28	22	412.1	94.3	336.4 439.8	338.1	284.6	380	293.2 294.2	.680 .679	.733 .741	1.0780 1.0913	3.0 3.2	29.13 26.98	28.06	
		.5 d	-12.0	316.0 313.8	32	22	639.2	141.4	661.2 803.2	732.2	314.9	345	314.6 321.2	.656 .650	.698 .695	1.0640 1.0692	2.0 2.3	27.13 28.30	27.72	
		.5 d	-10.2	409.8 412.8	140	26	892.8	184.0	2102.9 1501.5	1802.2	411.3	295	418.0 415.8	.544 .546	.557 .567	1.0054 1.0385	1.6 1.6	15.14 15.29	15.22	
		.5 d	-10.7	356.0* 384.0 409.4 402.8*	88	32	--	--	571.7* 694.0 1186.6 1974.4*	940.3	396.7	260	382.0 385.6	.583 .578	.597 .570	1.0240 .9862	2.6 1.6	28.46 22.10	25.28	*These densities were taken perpendicular to fall line and not parallel to it as were all other tensile samples
		.5 d	-9.7	432.4* 390.2 426.4 436.2*	82	--	--	--	1657.7* 875.4 -- --	875.4	390.2	220	431.8 404.0	.529 .559	.565 .588	1.0681 1.0519	2.6 3.2	27.53 25.80	26.66	
		.5 d	-7.6	397.0 401.0	62	--	--	--	830.7 --	830.7	397.0	170	415.0 405.0	.547 .558	.585 .622	1.0695 1.1147	4.1 4.9	30.63 32.73	31.68	
		-- e	-4.2	455.6 458.6	108	--	--	--	509.6 1028.8	769.2	457.1	111	473.2 469.8	.484 .487	.540 .557	1.1157 1.1437	6.4 8.9	37.64 40.17	38.90	
		1.5 e	-2.7	414.8 416.6	70	--	249.6	220.1	693.6 696.6	695.1	415.7	80	451.2 452.2	.508 .507	.527 .530	1.0375 1.0454	5.9 6.0	45.42 42.12	43.77	
		1.5 e	-1.4	491.0 495.2	142	--	665.7	351.0	1599.0 --	1599.0	491.0	30	498.0 499.8	.457 .455	.444 .456	.9724 1.0035	3.6 3.9	29.04 30.42	29.73	
2 Feb. '68	STATION 3 LINE A STAKE 7											45	Snow surface							
		.5 b	-18.1	282.2 270.0 301.0 288.6	22	1	258.2	79.9	172.4 -- 160.5 225.4	186.1	290.6	30	280.0 288.2	.695 .686	.711 .733	1.0230 1.0685	1.0 1.6	16.21 14.62	15.42	Initial hard slab.
		.5 b	-16.0	224.2 230.6 207.4	15	1½	121.4	53.4	119.6 180.1 162.0	153.9	220.7	12	244.0 239.8 236.4	.734 .738 .743	.729 .760 .766	.9932 1.0298 1.0310	1.2 1.3 1.8	21.06 21.06 30.04	24.05	
20 Feb. '68	STATION 3 LINE B STAKE 6											79	Snow surface							
		.7 bd	-7.2	250.6 240.4	8	1	95.0	38.6	143.1 94.9	119.0	245.5	65	267.8 266.4	.708 .710	.679 .721	.9590 1.0155	1.7 1.6	14.09 15.65	14.87	Not quite initial hard slab.
		1.0 db	-8.1	164.8 159.8	3	4	57.0	21.6	76.0 91.3	83.6	162.3	40								
		.6 d	-9.8	257.0 237.0	10	19	72.2	40.2	250.0 --	250.0	257.0	20	231.0 229.4	.748 .750	.763 .818	1.0201 1.0907	2.1 2.3	27.09 29.46	28.28	

Summary of Physical and Mechanical Properties of Alpine Snow--Mostly Less Than 2 Weeks of Age--continued

Date	Location	Grain size and type[1]	Temperature	Density	Ram no.	Age	STRENGTH INDICES Torque vane	Shear frame	Tensile (spin)	Average tensile	Average density	Height above datum	Density	Porosity n	Virtual porosity N	N/n	"a"[2]	Permeability	Average permeability	Remarks
		mm	°C	kg m^{-3}	kg	days	- -	gf cm^{-2}	- -	- -	kg m^{-3}	cm	kg m^{-3}					$\frac{cm^2}{sec\ (cm\ water)}$		
23 Feb.	STATION 4 LINE C STAKE 5											161	Snow surface							
'68		1.0 b	-7.8	67.6	2	1½	--	3.2	4.8	4.6	70.3	133	84.8	.904	.913	1.0100	3.5	88.19	103.22	Persistent soft snow
				73.0					4.4				80.6	.909	.943	1.0374	5.0	118.24		
		.5 bd	-7.2	183.8	3	4	5.7*	27.3	75.6	73.3	180.8	95	193.6	.788	.855	1.0850	5.0	51.31	55.12	*Reading suspect--snow too weak to give good reading.
				177.8					71.0				193.6	.788	.839	1.0647	4.3	58.92		
		.2 d	-7.8	310.6	33	5	201.4	86.3	696.8	632.5	312.5	60	312.8	.659	.708	1.0744	2.0	21.66	21.00	
				314.4					568.2				315.6	.655	.680	1.0382	1.9	20.34		
		.3 d	-8.9	254.0	26	11	123.5	71.8	273.2	399.2	248.2	20	243.8	.734	.756	1.0300	3.5	47.70	40.70	
				242.4					525.2				253.6	.723	.800	1.1065	3.8	33.69		
29-30 Apr.	STATION 3 LINE B STAKE 2											601	Snow surface							
'68		1.5 bd	-3.6	221.6	1	4	53.2	3.6	118.2	156.2	210.6	585	208.2	.773	.818	1.0582	3.6	37.61	33.60	Late season deep pit.
				199.6					194.2				210.6	.770	.795	1.0325	2.4	29.58		
		.5 bd	-5.7	334.2	40	--	283.1	88.6	749.7	752.4	335.4	550	357.0	.611	.623	1.0196	3.4	19.67	22.75	
				336.6					755.1				364.8	.602	.663	1.1013	4.0	25.83		
		.8 d	-6.5	371.2	65	--	672.0	142.0	1350.2	1255.4	363.8	480	366.2	.601	.644	1.0716	3.1	23.77	24.30	
				356.4					1160.6				369.4	.598	.674	1.1271	3.2	24.84		
		.3 d	-5.2	460.6	225	--	1920.0*	272.6	--	2507.3	467.4	340								*Reading was in excess of this but don't know how much.
				467.4					2507.3											

Martinelli, M., Jr.
1971. Physical properties of alpine snow as related to weather and avalanche conditions. USDA Forest Serv. Res. Pap. RM-64, 35 p., illus. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Data were taken in avalanche starting zones at an elevation of 11,700 feet in Front Range of Calorada within 14 days of deposition. Densities varied from 40 to 450 kg m^{-3}. A statistical criterion was used to identify snow with unusually high density for its age (initial hard slab) and unusually low (persistent soft snow). Initial hard slab, found in 15 percent af the pits, was correlated with moderate to high windspeeds, low temperatures, and presence of wind-transported snow. No good way was found to distinguish initial hard slab from dense older snow. Tensile strength from a spin test varied from 1.0 to 1712 grams force cm^{-2}. Strength increased with density but varied greatly for given density. Younger snows tended to be weaker than older snows of same density. Strength was also measured with shear box and shear vane. Ram resistance was higher for alpine snow than for snow of same density in the trees. Air permeability was an order of magnitude less than expected and varied with the low flow rate used. The ratio virtual porosity/porosity, which averaged 1.062, was of little value far identifying wind slab. Strength of snow of given density was greater for a certain permeability (texture) than for any other.
KEY WORDS: Avalanches, snow, weather, permeability, snow density.

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About The Forest Service. . . .

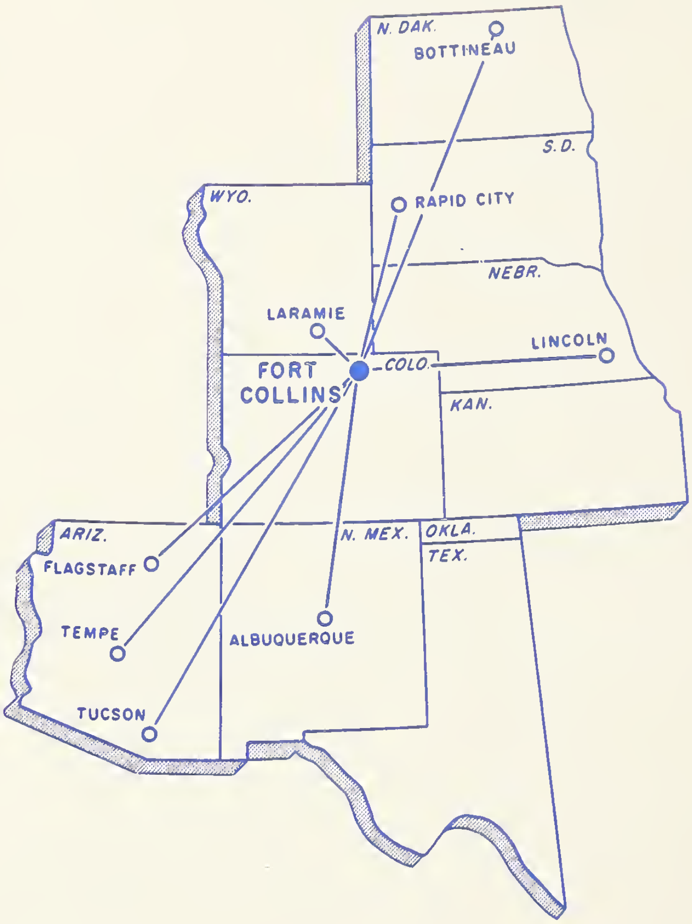
As our Nation grows, people expect and need more from their forests—more wood, more water, fish and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U. S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- *Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.*
- *Participating with all State forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.*
- *Managing and protecting the 187-million acre National Forest System.*

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.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